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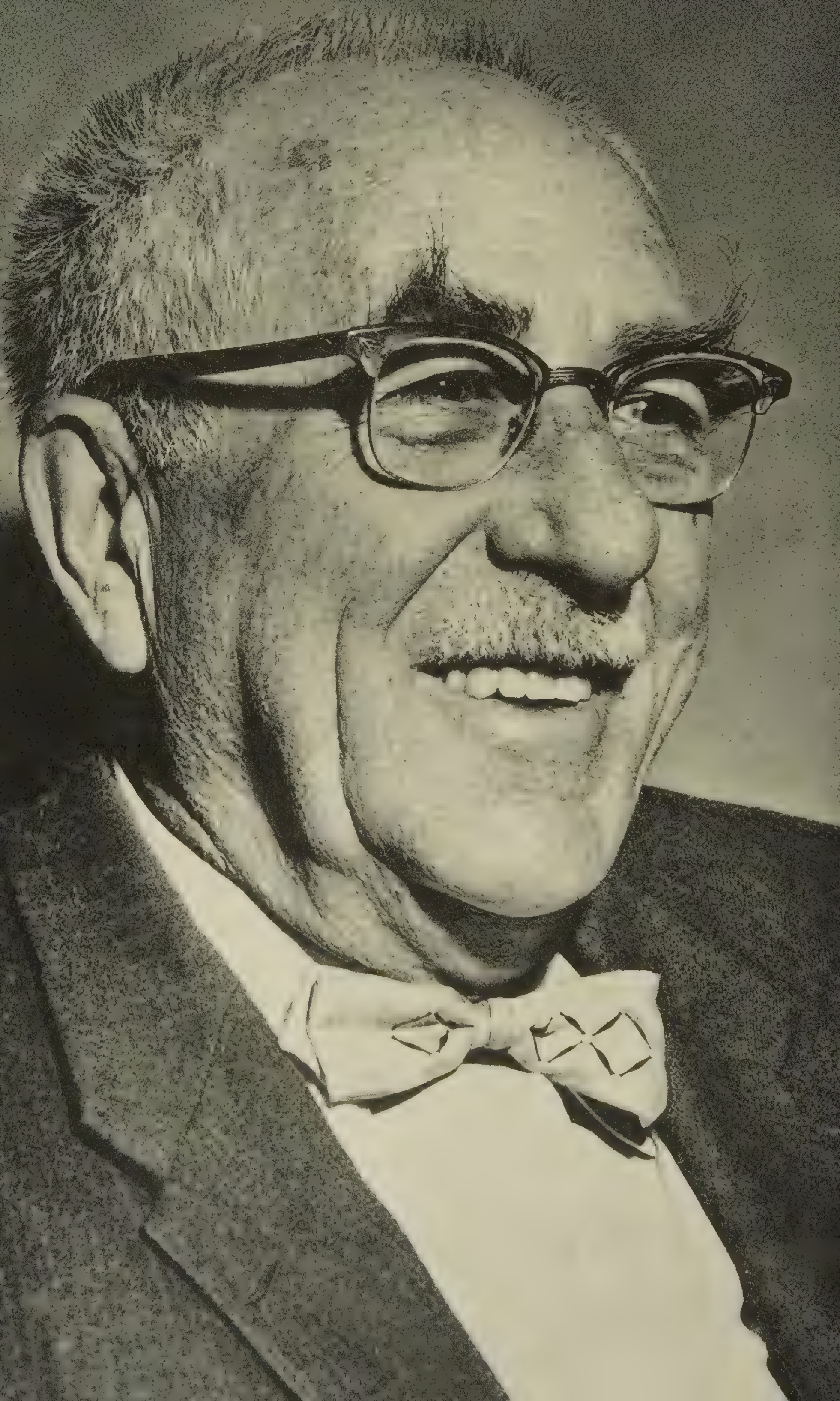

THIS VOLUME IS DEDICATED TO

THOMAS GORDON THOMPSON

ON THE OCCASION OF

HIS SEVENTIETH BIRTHDAY

BY SOME OF HIS FRIENDS AND ASSOCIATES IN APPRECIATION OF HIS PROFOUND INFLUENCE ON THE DEVELOPMENT OF OCEANOGRAPHY AND PARTICULARLY OF HIS MANY CONTRIBUTIONS TO OUR KNOWLEDGE OF THE CHEMICAL PROCESS WITHIN THE OCEAN

←*Photograph by Robert I. Petersen*

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THOMAS GORDON THOMPSON

Men of every civilization have extolled the fame and virtues of their teachers. An appreciation of learning and scholarship is, in fact, the mark of a civilization. Some men become pre-eminent not only because of their ability to contribute to the sum total of knowledge but by their facility in imparting their knowledge to others. Every University has its beloved Professors–scholars and teachers who are inspired with their subject and who, through the force of personality alone, are able to infect others with their enthusiasm and to color the lives of their students.

Such a man is Thomas Gordon Thompson, Professor of Oceanography and one-time Professor of Chemistry at the University of Washington, scientist, teacher, and friend of hundreds who know him as Tommy. There have been other Professors named Thompson; but to his students as well as to numerous scientists throughout the world, there is only one Tommy Thompson. This name identifies one of the world's leading oceanographers and one of the pioneers in the chemistry of the sea. The informality of his personality and his acceptance of this title does not lessen in any way the great respect that is held for his accomplishments. It is a measure of the affection that is felt by all who come in contact with him.

Tommy was born in Rosebank, Staten Island, New York, on November 28, 1888. He grew up in Brooklyn and attended Brooklyn Commercial High School. After graduation in 1906 he went to work as a laboratory assistant in the control laboratories of the American Brass Company–a step which set him on his initial course toward analytical chemistry. To this end he enrolled in Clark University and graduated with a Bachelor of Arts degree in 1914. Apparently following some attraction to a region he now refers to as "God's Country," he went directly to Puget Sound and the University of Washington for graduate work. Here he received a Master of Science degree in 1915 and a Doctor of Philosophy in Chemistry in 1918 (while in military service). In 1919 he became an Assistant Professor in Chemistry; in 1923, Associate Professor; and in 1929, Professor.

As head of the division of analytical chemistry at the University, Tommy established the courses in qualitative and quantitative analysis. These courses set a standard of performance that has indelibly marked the character of the hundreds of students who came under his watchful attention. His inexorable demand for integrity in what is the chemistry student's first real contact with laboratory experiments requiring independent judgment was an object lesson that all will remember.

A tribute to the significance of his work in the field of chemical education is found in the establishment at the University of Washington by Samuel G. Baker, one of his students, of the Thomas Gordon Thompson Fund for graduate fellowships in chemistry and chemical engineering.

Although his academic assignment during these years was in analytical chemistry, his research interests had turned to the chemistry of the sea; and, largely through his attainments in this field, the University was able to obtain a grant of $ 350,000 from the Rockefeller Foundation for construction of a building and the establishment of Laboratories of Oceanography. In 1930 Tommy was made first Director of the Oceanographic Laboratories, an appointment which he held for twenty years. Under his guidance, laboratories in Seattle and at Friday Harbor achieved world-wide recognition for accomplishments in the chemistry, physics, and biology of the sea.

He has been chairman of various national and international committees, notably the committee of the International Association of Physical Oceanography, appointed to establish standard units and procedures in studies of the chemistry of the sea. On several occasions he has been the U. S. National Academy of Sciences delegate in oceanography to various meetings of the International Geodesy and Geophysical Union. In 1948 his achievements were recognized when he was awarded the Alexander Agassiz Gold Medal by the National Academy of Sciences for his original contributions to the science of oceanography.

Of his publications–some 125 in number–eighty percent are in chemical oceanography. The development of his scientific interests can be traced in the titles of his publications. Initially they were in analytical and inorganic chemistry. In 1915 his imagination was captured by some work on the flow of salt water into Lake Union through the Lake Washington Ship Canal, and by 1927 he had begun a series of papers on the ionic ratios of sea water and the complex chemistry of the ocean. From 1927 on he was firmly committed to oceanography. In his general approach, Tommy has developed or improved the analytical method for determination of a particular constituent of sea water so as to give it the highest precision, has adapted the method for use at sea wherever practicable and has then used the method for analysis of naturally occurring waters to describe and account for the distribution of the subject constituent in nature.

His work and that of many of his students provide evidence of efforts to establish the comparative invariance of the composition of sea water in various parts of the world and to elucidate the chemistry of changes that occur in minor elements. Precise determination of the ratios of the major ions has proved the constancy of composition of "sea salt" and has established the basic chemistry for studies of the numerous trace elements that play an important role in the nutrition of marine organisms. A series of papers on these elements deals with iron, silicon, manganese, aluminum, lithium, nickel, boron, fluorides, phosphates, and the dissolved gases. An early paper treats of the radioactivity of sea water and another considers the distribution of isotopes. All of these contributions point to the work of a mind intent on a complex subject and yet at the same time equally alive to the obligation of science to simplify, to generalize, and to find related meanings in apparently unrelated facts. Almost every present-day article treating the density or the electrical conductivity of sea water makes reference to the basic work of Thompson and his collaborators in this field. It is difficult to find a current paper treating the various chemical constituents in sea water on which Tommy has worked that do not refer to his earlier papers. Repeated requests for reprints of his articles years after the supply of many has been exhausted attest to the lasting value of his studies.

Not all of his students have become oceanographers or "sea-water" chemists. This is not from lack of inclination, because there were few who came under his tutelage who were not inspired by his enthusiasm for the sea. But Tommy trained chemists; and the field of chemistry offered opportunities that were sometimes more attractive than those in oceanography. Today, many of his students are in responsible positions in the academic world and in industry, but many have a nostalgia for their past association with oceanography and their personal relationship with Tommy. The force of his personality was always present to inspire a disheartened graduate student.

His personality is complex. He is a discriminating philatelist with a collection acquired over many years. He is a loyal officer of the Chemical Warfare Corps and his service during two world wars is a story in itself. He has had his share of tragedy, but the ups and downs of life have been met with equal strength of character. He has encountered the vicissitudes of an active life with courage, and he has received the honors due him with modesty.

No account of Tommy would be complete without mention of the "Catalyst"–the 75-foot, diesel-driven floating laboratory that represented an attempt to crowd all possible devices for study of the sea into a minimum volume and to combine them with living quarters and a chemical laboratory. The final result was a trifle topheavy, which accounted for the great amplitude of roll and the prevalence of *mal de mer* among the devoted passengers and crew. Tommy–sometimes called "The Admiral" under these circumstances–was a man of courage, the first to master his discomfort and to carry on in the face of adverse winds and waves. Seeing him in oilskins on the somewhat perilous platform hanging over the ship's side, superintending the collection of a water sample from the depths, was to sense his persistent interest in the mystery of the sea. Epics have been written about the men "who go down to the sea in ships," and legends about them and the spell of the sea are wonderful indeed. But here is a man who has loved the sea in a different way and who has sought to penetrate her secrets by the scientific method.

One facet of Tommy's many-sided character has found expression in his purchase of McConnell Island–one of the beloved San Juan group–and its development as a home. This has been a family project over many years and has resulted in a house of driftwood and native stone set down by an inlet ringed with evergreens and the bare rocks of the shoreline. The ever-changing picture of land and sea, the wild beauty of the islands, the dramatic sunsets, and the presence of salt water on every side have their permanent place in the life of the owner, who has become a part of them himself.

One might wonder that Tommy–so gregarious, so much a part of the world himself–should take himself away to a spot that would delight the heart of a hermit. McConnell Island, however, is anything but a hermitage. Hundreds of visitors from all over the world visit the island each year. And here they find something of their own, whether their interests be the chemistry of the sea, the life of purple algae, the history of the San Juans, their geology, or merely a love of natural beauty and friendship for the owner.

McConnell Island is alive with the personality of Tommy Thompson. Who else would call the various parts of his domain such names as "Sunken Heights" and "Hernia Hill" and "Mosquito Bight"? And where else would one find, on such a limited area, a railroad–in miniature, to be sure, and a family project–that is real enough to serve a useful purpose in conveying materials round about and fast enough to have a genuine wreck for visiting celebrities?

Part and parcel of Tommy's character is a unique sense of humor, quite unlike any other. Subtle and involved, it may take the form of a far-fetched pun requiring a long build-up. To his technical associates, it may have a technical flavor, but it will also have a human touch that is penetrating but invariably kindly. He tells stories in a way that conveys his own personal enjoyment and makes the listener a participant.

Part of his charm is the trace of a Brooklynese accent that the years have never completely eroded and that still plays havoc with the letter "r". This converts a bird into a boid but leaves the idear intact.

And now he is of an age where he can look upon a life spent usefully in the service of Science. In following this life, he has won the respect of his fellow scientists, and–perhaps more important–the love and affection of those who have been his students and colleagues. They wish him continued health and happiness.

B. D. THOMAS
June 4, 1959

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INORGANIC SUSPENDED MATTER IN SEA WATER

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ABSTRACT

The suspended matter in sea water has been separated with membrane filters (down to 0.1 μ A.P.D.); the inorganic fraction, determined by ignition, has been partly analysed. The methods used are briefly described. An appreciable quantity of finely divided claylike material was found, and it is suggested that, by adsorption of organic matter from the water, this may support the bacterial flora. Samples taken regularly from the English Channel show a seasonal variation, the quantity found being greatest in winter and ranging from 0.16 to 1.20 mg/l, the mean being 0.6 mg/l. The analyses showed approximately 43 % SiO_2, 13 % Fe_2O_3, and 13 % Al_2O_3. Silicon in suspension generally exceeded that in solution.

At three deep water stations in the eastern Atlantic, rather smaller quantities of suspended matter (0.05–1.00 mg/l) compared to the Channel were found. Some of the figures may be high owing to precipitation of calcium carbonate during storage. In the upper waters silicon in suspension exceeded that in solution, but below c. 100 m the reverse was the case. The amount of iron in suspension resembled that found by direct analysis. Some results for aluminium in suspension show quantities around 37 μg Al/l in the English Channel and around 12 μg in the eastern Atlantic.

INTRODUCTION

Suspended matter in sea water has been studied by optical methods and by filtration, direct determination and analysis. Jerlov (1950, 1951, 1953, 1955), who has used the Tyndall effect to measure particle distribution in several areas of the ocean, has shown that it may be used to characterise water masses. Kullenberg (1953), using Jerlov's light-scatter data, has estimated the oceanic concentration of suspended matter as being not more than 0.056 mg/l. Tsujita (1953a, 1953b, 1955), using ordinary and electron microscopes, reported qualitative and descriptive studies.

Pettersson (1943) used glass-frit filters and measured dried organic and inorganic material in Gullmar Fjord. Krey (1950a, 1950b, 1952) used paper and membrane filters to determine total dried material in northern European waters. Armstrong and Atkins (1950) determined the inorganic part of the suspended matter retained by fine filter paper and reported some partial analyses for surface water samples taken 20 miles offshore from Plymouth.

Fox, *et al.* (1952) used absorptive filters to determine organic matter (calculated from carbon and nitrogen determinations) in northeastern Pacific waters. Goldberg, *et al.* (1952), using membrane filters, measured total and inorganic suspended matter in water from the same area. Atkins, *et al.* (1954) used membrane filters, measured the albedo of the discoloured filters as an index of suspended matter and reported the results of microscopic examinations. Jones and Wills (1956) also used membrane filters and found a linear relationship between the concentration of suspended matter and the attenuation coefficient for light, measured with a specified instrument.

The work described below was undertaken in 1951 and 1952 to find the quantities of suspended inorganic material in subsurface waters in the English Channel and in deeper waters of the Atlantic.

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APPARATUS AND UNITS

Collecting Gear–Wooden bucket (later polyethylene was used), Nansen-Pettersson bottle, or Ekman reversing hydrographic bottle.

Sample Bottles–5 gallon carboys, Winchester bottles (2.7 l) or Pyrex Erlenmeyer flasks (2.2 l). These containers were reserved for this work and kept dust-free.

Filtration Apparatus–"Stefi" filter with glass-frit disc, used as described by Cole and Jones (1949) except that the supporting filter paper was omitted.

Membranes–"Gradocol" membranes of 4 cm diameter, made by the method of Elford (1931), were supplied by The Wright-Fleming Institute, St. Mary Hospital, London. The average pore diameter (A.P.D.) of each batch was given; for all except the preliminary experiments it was between 0.47 and 0.51 μ or 0.09 and 0.12 μ.

Spectrophotometer–The "Unicam" S.P. 500 instrument was used with slit widths of 0.05 and 0.03 mm at 390 and 465 mμ respectively.

Units–Inorganic suspended matter is reported in mg/l, silica as mg SiO_2/l, iron as μg Fe/l, aluminium as μg Al/l.

EXPERIMENTAL

PRELIMINARY EXPERIMENTS

These were intended to determine whether membrane filtration of 2 l of water and semimicro analysis would give results comparable to the paper filtration with 20 l quantities used in previous work (Armstrong and Atkins, 1950); also, they were intended to test the reproducibility of the methods.

In the first experiment, six surface samples were taken with the usual precautions, using a wooden bucket. Two were in carboys (25 l), two in glass bottles (2 l), and two in conical pyrex flasks (2 l). The carboy samples were filtered on paper, the residue being washed with 5 % ammonium nitrate solution instead of distilled water and acetone as formerly. By this means an effort was made to avoid the disruption of plant cells and peptisation of fine material which may occur with distilled water. The 2 l samples, filtered successively on membranes of 1.0 and 0.2 μ A.P.D., were washed with ammonium nitrate. All residues were ignited at 500° C and weighed in platinum. Before proceeding with the usual analysis of the paper-filtered samples, chloride was determined by titration with mercurous nitrate, the residue being then evaporated and ignited to volatilise the reagents so that the analysis would proceed by standard methods. The ash of the material on the membranes was fused with sodium carbonate, dissolved in water, and neutralised with hydrochloric acid, after which silicon was determined colorimetrically on an aliquot portion. Another portion was used for colorimetric determination of iron, using 1:1 bipyridyl. A second experiment was done with papers and membranes, using water taken from a depth of 10 m by suction into carboys through a hose, for comparison with water from the same depth taken with a Nansen-Pettersson bottle. A surface sample was also taken as well as duplicate samples at 50 m.

Results of these experiments, given in Table I, show quite good agreement between the carboy and 2 l samples as well as fair reproducibility. The amounts of salt found show that the washing is reasonably effective, since some chloride is to be expected from the contents of plant cells or small animals. In three of the analyses the quantity of inorganic matter retained by each size membrane was determined; 6, 5, and 10 $^0/_0$ of the totals were caught on the 0.2 μ membrane. This is an appreciable fraction, and for the work which followed, average pore diameters of 0.5 and 0.1 μ were chosen as the finest which could conveniently be used; with these, filtering rates were roughly 30 min and 4–8 hours for 2 l samples for the respective sizes. The method of filtration was standardised

TABLE I. SUSPENDED MATTER IN SEA WATER; COMPARISON OF ANALYSES

Date and Depth (m)	*Volume (l)*	*Filters*	*Inorganic Suspended Matter (mg/l)*	*SiO_2 ($^0/_0$)*	*Fe_2O_3 ($^0/_0$)*	*Salt (from chloride) ($^0/_0$)*
1951						
26 February						
0	25.7	Paper	0.82	38	12	8
0	25.8	Paper	0.85	36	14	3
0	2.72	1.09 μ and 0.21 μ membrane	0.73	47	14	—
0	2.72		0.83	42	10	—
0	2.28		1.20	42	11	—
0	2.22		0.79	44	14	—
28 March						
10	25.4	Paper	0.85	35	8	—
10	25.7	Paper	0.82	55	9	—
10	2.31	1.09 μ and 0.21 μ membrane	0.87	44	7	—
10	2.22		0.82	40	12	—
50	2.20		0.98	40	6	—
50	2.22		0.92	41	9	—

from 24 April 1951, with some exceptions mentioned below, but the methods of analysis continued to change somewhat as more convenient techniques evolved. Since the methods are all conventional they are described only briefly.

METHODS

Collection of Samples. All obvious methods of avoiding contamination of samples by dust and dirt were used. In dry weather the deck of the ship was hosed down for some distance all round the sampling position.

Filtration. This was done within three days of collection of samples with the important exceptions noted below. The whole volume taken was used. Carboy samples were filtered on paper and the residue was analysed as described by Armstrong and Atkins (1950). The 2 l samples were filtered first through a 0.5 μ membrane. When all the water had passed through, three or four successive portions of about 100 ml were used in succession to wash out the sample bottle, the inside of which was freed of adhering material by cleaning with a rubber tipped rod. The filtered water was returned to the bottle. The membrane, washed with three 20 ml portions of 5 $^0/_0$ w/v ammonium nitrate solution (neutralised with ammonia to phenol red and filtered through 0.1 μ membrane), was set aside on filter paper, spotted with glycerol (50 $^0/_0$ v/v) and kept under cover until ignited. The water was refiltered through a 0.1 μ membrane, which was treated similarly. The volume of water was then measured and recorded.

Ignition. This was in platinum crucibles for 30 min at 500° C. The spotting with glycerol kept the membranes moist and prevented flaring and *dusting*. Weights were recorded to the nearest 10^{-5} g and were corrected for the blank on the membrane and glycerol and for the average loss of platinum on ignition.

Silicon. Silicon was found by loss on treatment with hydrofluoric acid.

Iron. The residue from the silicon determination was fused with potassium bisulphate; the melt was dissolved in hydrochloric acid (10 $^0/_0$ v/v) and made to a known volume. Iron was determined colorimetrically with thiol-acetic acid until August 1951, when the following method, which also determined aluminium, was adopted.

Iron and Aluminium. After extraction of the bisulphate melt, as before, the solution was neutralised to phenolphthalein with ammonia and buffered to pH 5, after which iron and aluminium were extracted as the oxinates by shaking with a chloroform solution of 8-quinolinol (1 $^0/_0$ w/v). The absorbencies of the extract were measured at 390 and 465 mμ to determine iron and aluminium. Blanks were carried through all stages. The method is almost interference-free for iron, but a number of elements can interfere with the aluminium determination. There was no reason to suppose, however, that interference would amount to more than about 1 $^0/_0$ of the ash.

Calcium. This was done on one set of samples only, after the oxine extraction, by precipitation as oxalate and ignition to carbonate. Since the samples had by then had considerable handling and since weights of less than 1 mg $CaCO_3$ were found, no great accuracy is claimed.

RESULTS

Samples were taken monthly at the International Hydrographic St. E1, 20 m offshore in the English Channel, from 26 February 1951 to 11 March 1952. The inorganic suspended matter and its included silicon as SiO_2 are shown in Fig. 1.

Some samples taken from R.R.S. DISCOVERY II in deep water were also examined (Table II). Some of the deeper samples were composite ones from adjacent depths, as is shown. Samples from Sts. 2918 and 2927 were filtered on the ship within three days of collection, but those from St. 2929 were done at the Plymouth Laboratory 11–18 days after sampling. It was found necessary to use the double filtration (0.5 followed by 0.1 μ membrane) only for samples down to 100 m; time was saved and extra manipulation avoided by filtering the cleaner samples from deep water on a 0.1 μ membrane only. In these samples the suspended matter was just visible on the membrane as a faint greyish-brown stain.

When the analyses for SiO_2, Fe_2O_3 and Al_2O_3 had been completed, it was obvious that a large part of the suspended matter at St. 2929 was unaccounted for, therefore these samples were then analysed for calcium. The quantities found made up most of the deficiency. Because these samples had been stored longer than the others, it was thought possible that at least part of the calcium found had been precipitated after collection of the samples, as in one case

Station, Date and Location	*Depth (m)*	*Inorg. Suspend. Matter (mg/l)*	*Silicon (μg SiO_2)*	*Iron (μg/l)*	*Aluminium (μg/l)*	$SiO_2 + Fe_2O_3 + Al_2O_3$ *(mg/l)*	*Dissolved Silicon (μg/l SiO_2)*	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	$CaCO_3$ (%)	*Total (%)*	*Si : Al (atoms)*
2918	0	0.11	50	7	6	0.08	50	50	10	11	—	71	15
3 June 1952	20	0.21	150	6	8	0.17	70	70	4	7	—	81	34
49°02′ N 15°19′ W	100	0.63	430	17	23	0.50	310	68	4	7	—	79	33
Sounding 4720 m	960	0.88	280	43	49	0.45	780	33	7	11	—	51	10
	1820	0.27	60	23	14	0.18	840	23	12	10	—	45	8
	2620	0.33	80	15	16	0.14	1680	25	7	9	—	41	9
	3730	0.14	50	23	10	0.10	2700	35	26	12	—	73	7
2927	0	0.21	50	66	6	0.17	60	25	45	6	—	76	14
8 June 1952	20	0.36	—	26	13	—	70	—	10	7	—	—	—
43°23′ N 19°23′ W	100	0.17	—	19	4	—	220	—	16	5	—	—	—
Souuding 6000 m	960	0.12	50	5	6	0.07	720	46	6	9	—	61	17
	1420	0.11	70	8	8	0.09	840	61	10	14	—	85	15
	2400*a*	0.06	80	—	4	—	1140	80	—	14	—	—	—
	3000*b*	0.15	100	6	2	0.12	1800	70	6	2	—	78	12
	4100*c*	0.05	40	6	2	0.05	2500	78	19	9	—	106	30
	5200*d*	0.09	70	25	7	0.12	2700	80	40	15	—	135	18
	5880	0.17	70	17	12	0.12	2700	40	15	13	—	68	10
2929	0	0.54	350	22	14	0.42	60	66	6	5	18	95	44
10 June 1952	20	0.61	110	26	13	0.24	60	30	6	4	27	67	46
44°30′ N 15°26′ W	100	0.76	80	18	8	0.12	210	11	3	2	60	76	19
Sounding 5500 m	980	1.00	80	16	14	0.13	720	8	2	3	60	73	9
	1840	0.15	60	9	12	0.09	840	39	9	15	53	116	9
	3000*e*	0.30	60	7	9	0.08	1980	19	3	6	36	64	11
	3600*f*	0.50	70	13	9	0.11	2400	14	4	4	47	69	12
	5310	0.57	90	33	17	0.16	2800	15	8	6	50	79	8

NOTES: Equal volumes from	*a*)	*b*)	c)	*d*)	*e*)	*f*)
	2180 m	2770 m	3580 m	4750 m	2180 m	3450 m
	2380	2890	3980	5050	3010	3650
	2580	3120	4300	5380	3210	3850
		3350	4460	5580		

observed before (Armstrong and Atkins, 1950: 140) when an unusually high calcium content of 70 °/₀ was found in a sample which had been kept overlong. For best comparison, the sums of the other constituents (silica, ferric oxide, and alumina) have been tabulated separately where possible. Also recorded are the relevant concentrations of dissolved silica (as determined by reaction with molybdate) and silicon aluminium ratios.

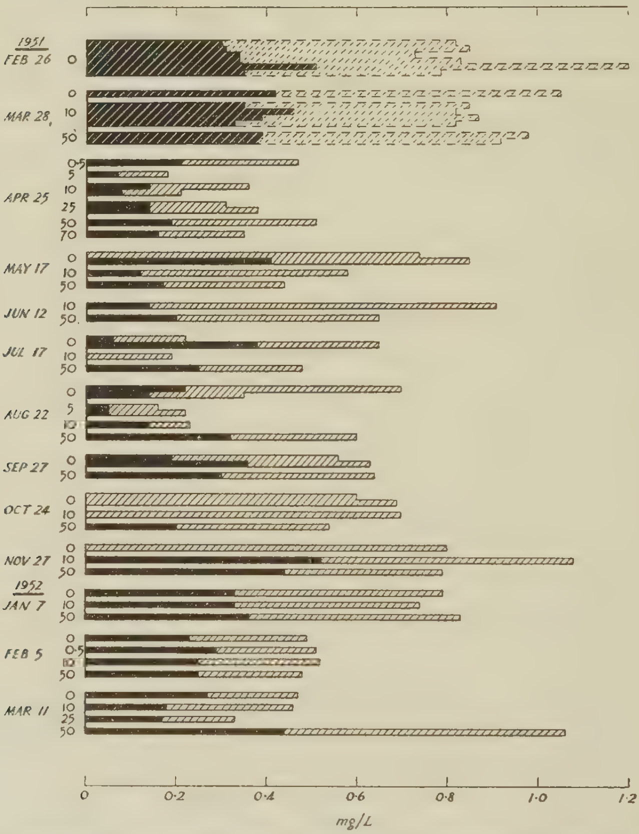

Figure 1. Suspended matter and silicon (solid portion of histogram) in mg/l at International Hydrographic Station E1 (50°02′ N, 4°22′ W) February 1951 to March 1952; filtered on 0.5 and 0.1 μ A.P.D. membranes excepting February and March 1951, when 1.0 and 0.2 μ A.P.D. were used.

DISCUSSION

General. The large proportion of calcium (returned as carbonate) in the samples from DISCOVERY St. 2929, which had been stored during warm weather for longer than usual, casts some doubt on the validity of the figures for total inorganic suspended matter and on their representation of conditions in the sea. Some precipitation may have taken place in all samples after collection. Rise of temperature and release of pressure may cause sea water samples to become supersaturated with respect to calcium carbonate, and the particulate matter would probably provide many nuclei for crystallisation.

This possible artifact may have been partly controlled, since most of the samples were filtered shortly after collection. Inspection of the analyses shows that generally the effect could not have been great, since calcium carbonate could rarely exceed 50 °/₀ of the suspended matter even if it accounted for all the deficiency in the analyses.

Means of some of the data are given for convenience. It should be stressed that these are not true means since the sampling is biassed and since surface samples carry more weight than they should.

Total Inorganic Suspended Matter. For the English Channel, quantities of 0.16 to 1.20 mg/l (mean of all determinations 0.61) were found. Fig. 1 shows the seasonal variation, more being found during winter months than during other seasons. This effect is not likely to have been influenced by calcium precipitation following collection of samples, which is more probable in summer. It is simply explained as being the result of increased land drainage and turbulent mixing of bottom deposits in winter. There is an occasional tendency for the quantity of suspended matter to be higher at the surface than at subsurface depths.

At the deep water stations, concentrations varied from 0.05 to 1.00 mg/l, but the highest figures at St. 2929 were certainly due to high calcium content and may be put down to the prolonged storage. This effect may also be suspected at 960, 1820, and 2620 m at St. 2918.

$SiO_2 + Fe_2O_3 + Al_2O_3$. This sum has been entered in Table II where possible. Apparently it shows more regularity than the total suspended matter.

Silicon. At St. E 1, concentrations of 54 to 520 μg SiO_2/l were found. The seasonal variation is seen in Fig. 1; the decrease in summer goes with an increased diatom population. Except for one occasion, the silica in suspension exceeded that in solution, the latter ranging from 26 to 190 μg SiO_2/l [means for the whole water column (Armstrong, 1954)]. On 22 August 1951, silica in suspension at 5 and 10 m was 50 μg SiO_2/l whilst dissolved silica was about twice this value.

It is possible that resolution of suspended silica (much of which must be in diatoms) is rapid at times during the summer months.

At the deep water stations, suspended silica is not in excess except at or near the surface, but even in deep water it amounts to 2–10 $^0/_0$ of that in solution.

Iron. At the English Channel station there is a tendency for iron concentrations to be greater in winter than in summer, with higher values at the surface. The concentrations varied from 10 to 145 μg Fe/l, the mean being about 50 μg Fe/l. These results are in agreement with those of direct determinations for this station in 1955 and 1956 when there was an unbiassed mean of 35 μg Fe/l for two years (Armstrong, 1957).

At the deep water stations the range was 5–66 μg Fe; these values are comparable with those found directly for deep water stations in the Bay of Biscay (Armstrong, 1957).

Aluminium. From August 1951 to March 1952 the range was 8–107 (mean 37) μg Al/l. In deep water the range was 2–49 (mean 12) μg Al/l. These values may be compared with an estimated concentration for the open Pacific of about 30 μg Al/l (Arrhenius, 1954).

Silicon:aluminium Ratios. The atomic ratios for the deep water stations vary from 8 to 46 and show a great excess of silicon compared with ratios for any of the common clay minerals.

CONCLUSIONS

It has been shown that an appreciable quantity of finely divided suspended matter exists both in offshore waters in the English Channel and in the open ocean. Because of its claylike nature, it is likely to be strongly absorbent, both of inorganic and organic substances in the water, and it may well be the chief support of the rather sparse bacterial flora in sea water. Its relatively large silica content may influence the silicon cycle and the growth of diatoms, at least in upper waters.

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MARINE SEDIMENTS OF PRINCE OF WALES STRAIT AND AMUNDSEN GULF, WEST CANADIAN ARCTIC[1]

BY

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ABSTRACT

Fifty-two marine sediment samples from Prince of Wales Strait and Amundsen Gulf have been analyzed for properties such as grain size and rock and mineral composition. It appears that the distribution of the various sediment types in the area investigated is markedly influenced by both stream location and sea ice.

INTRODUCTION

The marine sediments described in this paper were collected during the 1953 Beaufort Sea Expedition, sponsored by the United States Navy. This was the first expedition to systematically investigate the marine deposits of Amundsen Gulf and Prince of Wales Strait (see Fig. 1).

Geographic Description. Previous expeditions have provided considerable information concerning the geography and geology of this general area (Carsola, 1954a; Washburn, 1947; Chipman and Cox, 1924). The mainland east of the Mackenzie River to Cape Bathurst is a flat swampy plain, and from Dolphin and Union Strait east to Sherman Inlet on Adelaide Peninsula it is generally low and deeply indented. But in the vicinity of Tree River and Cape Barrow on Coronation Gulf the terrain is rugged. The Coppermine is the largest of several rivers in this area.

Prince of Wales Strait separates Banks Island from Victoria Island. In the southern portion of Victoria Island and along Prince

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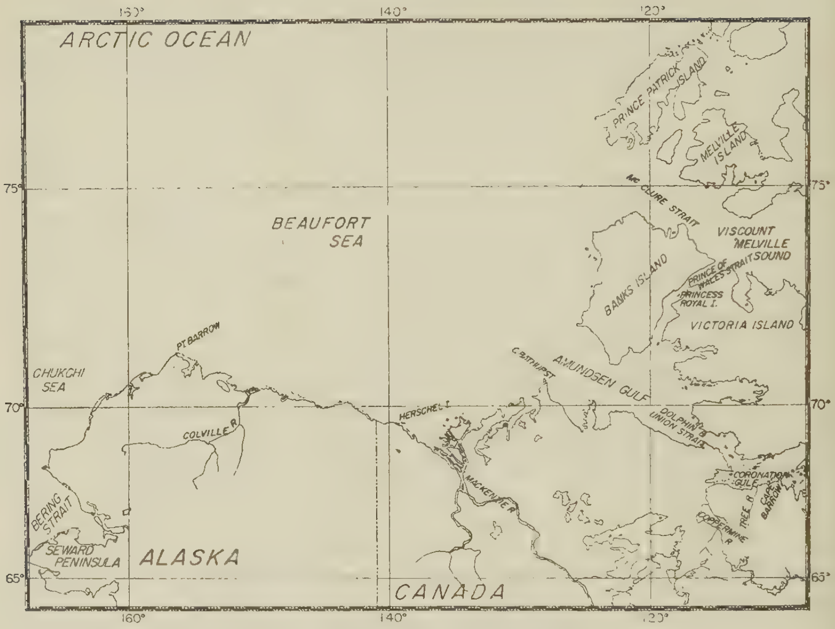

160°
140°
120°
75°
70°
65°
ARCTIC OCEAN
BEAUFORT SEA
PRINCE PATRICK ISLAND
MELVILLE ISLAND
MC CLURE STRAIT
VISCOUNT MELVILLE SOUND
BANKS ISLAND
PRINCE OF WALES STRAIT
PRINCESS ROYAL I.
VICTORIA ISLAND
PT. BARROW
CHUKCHI SEA
C. BATHURST
AMUNDSEN GULF
DOLPHIN & UNION STRAIT
HERSCHEL I.
COLVILLE R.
MACKENZIE R.
CORONATION GULF
CAPE BARROW
TREE R.
COPPERMINE R.
BERING STRAIT
SEWARD PENINSULA
ALASKA
CANADA

Figure 1. Map of the West Canadian Arctic.

Albert Sound the topography is generally under 300 feet, but inland elevations of about 2000 feet have been reported. In the Walker Bay area, steep shores rise to over 1000 feet. The near-shore area along Prince of Wales Strait is generally under 200–300 feet, these elevations increasing inland.

The southern part of Banks Island from Nelson Head east to Cape Lambton and then north to Thesiger Bay is characterized by steep cliffs composed of a sedimentary sequence capped with basalt which may rise to more than 1500 feet; in the southwest corner there is a plateau over 2000 feet high. The coast region from Nelson Head to DeSalis Bay and eastward is low-lying while inland the elevation increases gradually to a maximum of about 1000 feet. The Prince of Wales Strait shore area is generally under 200 feet.

Both Banks and Victoria Island show evidence of glaciation (Washburn, 1947; Porslid, 1950). An esker has been observed on the high plateau of Nelson Head and Cape Lambton, and eskers, striated stones, and erratics have been found on southern and eastern Banks Island. In the Walker Bay region of Victoria Island, also glaciated, the high plateau to the north has in the limestone many large striations which trend northwestward. Terraces on both islands up to approximately 600 feet indicate isostatic adjustment following glaciation. Although it is known that the lower terraces are former strand lines, many of the higher terraces are of doubtful origin.

Oceanographic Description. The region eastward from Icy Cape, Alaska, including Amundsen Gulf, is covered by unnavigable shorebound sea ice for about 9 to 10 months of the year (U. S. Hydrographic Office, 1946), and permanent polar ice is located approximately 40 to 60 miles north of Point Barrow, Alaska. In July the heavy ice begins to dissipate in the southern Chukchi Sea, at the mouth of the Mackenzie River, and south of Victoria Island in Dolphin and Union Strait and Coronation Gulf. During August a narrow strip of navigable ice appears along the continental shore from the Chukchi Sea to Hershell Island, just east of the Mackenzie River mouth. The strip gradually widens eastward and Amundsen Gulf is usually ice-free in August. In early August 1953 it was necessary to search for open leads only a few miles from shore in the region east of the Mackenzie River.

By September the ice begins to move back against the shore and may become land-fast at Point Barrow, although Amundsen Gulf is usually still open. Prince of Wales Strait may or may not be navigable. In October the sea again becomes ice-bound.

The wind direction and force is an important factor in the ice distribution. In August and September of 1953, during periods of north and northwest winds, Prince of Wales Strait was generally ice-bound, but during periods of southeast winds or calm weather the ice was either absent or scattered.

Wave action is usually negligible due to the relatively short fetch. The tides are mostly under one foot although Stefansson (1921) has recorded 6- to 8-foot wind tides along the western coast of Banks Island due to strong west winds. Low tides may also be associated with east winds. The currents are poorly developed and not well understood (U. S. Hydrographic Office, 1951; Carsola, 1954a).

In the western Arctic most of the soundings have been obtained off the Alaskan coast. Carsola (1954a, 1954b) has discussed the relief of the Continental Shelf and adjacent areas of the Beaufort and Chukchi seas. The Continental Shelf of the Beaufort Sea, terminating at about 30 to 40 fathoms, shows the effects of local glaciation just west of Amundsen Gulf. Shelf glaciation is to be expected in the eastern Beaufort Sea since there is ample evidence of glaciation on the southern parts of Banks and Victoria Island.

Amundsen Gulf, approximately 500 to 700 feet deep, is apparently a trough-like basin oriented WNW. Prince of Wales Strait, with a maximum depth of about 240 to 450 feet, is much shallower than Amundsen Gulf or McClure Strait.

Sediment Ice-Rafting. Ice-rafting of one type or another in the Arctic has been discussed by Nares (1878), Bancroft (1905), Stefansson (1921), Kindle (1924), Chipman and Cox (1924), Nichols (1936), Deevey (1939), Washburn (1947), LaFond *et al.* (1949), Emery (1949), Fletcher (1950), Carsola (1954a), and others.

Ice-rafting is capable of transporting sediment far from its source. In the Chukchi Sea, mud-laden ice was observed almost 200 miles from the nearest land. In early August 1953 brown sediment-laden ice was abundant in the vicinity of the Mackenzie River mouth, but in September it had disappeared; it had melted or been carried away by winds and a westerly current.

Ice islands provide an excellent means for long range sediment transport. These islands are fragments of shelf ice from Ellesmere Island over 1000 miles to the east (J. O. Fletcher, personal communications). One such island, $^1/_4$ mile wide by $^1/_2$ mile long and about 100 feet thick, was observed in Prince of Wales Strait. The surface was coated with a layer of micaceous sediment. The schists and gneisses on northern Ellesmere Island may have been the source of this sediment.

The sediments may become a part of sea ice by the following principal means:

1) Grounded sea ice freezes at the base and includes sediments. Repeated melting of the upper surface and refreezing at the base gradually bring sediments to the surface.

2) Land-fast ice picks up beach sediments on the bottom and landslides or slumping add material to the ice surface. Numerous instances of this were observed in Prince of Wales Strait; in some cases till-like soil completely covered the ice.

3) Since river ice breaks up earlier in the spring than sea ice, river waters flow out over the sea ice and deposit their load. Examples of this were observed at the mouth of small intermittent

streams on the east side of Banks Island. The ice island is another example.

4) Sediment-laden sea water freezes and facilitates ice-rafting, particularly in the vicinity of large rivers, such as the Mackenzie, where the water is quite turbid.

5) Rivers themselves, *e. g.*, the Mackenzie, carry a great deal of sediment-laden ice to sea.

6) The wind also adds to the sediment and debris on and in the ice.

LABORATORY METHODS

Grain Size Analysis. In general, the methods of mechanical analysis described by Krumbein and Pettijohn (1938) have been used. However, certain procedures deviated from the above methods.

The marine salts were removed from the sediments by washing the sample with distilled water, centrifuging and siphoning off the liquid. The samples were then mixed for 10 minutes in a 0.1 g/l solution of sodium lignosulfonate (Marasperse N) by means of an electric mixer. The wet mixture was passed through a 0.062 mm sieve, after which it was washed with the sodium lignosulfonate solution into a 1000 ml pipetting cylinder. The filtrate was then brought up to the 1000 ml volume. The coarse material, larger than 0.062 mm, was dried, weighed, and run through a series of sieves (32 to 0.062 mm). The size fractions were weighed and the fine pan fraction that remained was added to the cylinder. The filtrate was then analyzed by the standard pipette method of Krumbein and Pettijohn (1938).

Microscopic Examination. The coarse fraction was examined with a binocular microscope to identify the principal minerals and rock fragments. A representative portion of each fraction having a size greater than 0.062 mm for each sample was counted on a grid until a total count of approximately 500 was reached.

SEDIMENT DESCRIPTION

Surface sediment samples were collected in 37 localities: six in Amundsen Gulf and 31 in Prince of Wales Strait. The sediment generally consisted of a reddish-brown top layer a few inches in thickness and of an underlying portion that was usually gray. In view of this, 15 samples were separated into a top and bottom

TABLE I. SEDIMENTARY PARAMETERS

Sample*	Location		Median Diam.		Sorting		Percent			
No.	Lat. North	Long. West	mm	Ø	Trask	Ø	Gravel	Sand	Silt	Clay
1	70°45.0	127°33.2	0.043	4.65	1.02	2.25	0.20	78.2	3.7	18.0
2	70°12.7	124°35.0	0.012	6.30	4.00	2.45	0.10	37.6	45.4	16.9
3B	70°39.0	124°10.0	0.005	7.65	2.80	2.40	—	12.3	60.3	27.4
4	70°50.0	123°24.0	0.012	6.67	3.20	2.30	0.10	24.9	54.5	20.5
7	71°09.5	122°32.2	0.062	4.00	1.30	0.70	1.20	79.0	14.7	5.1
8	71°25.4	120°35.2	0.029	5.10	4.40	3.80	—	29.2	50.9	19.9
11	71°34.1	119°11.0	0.062	4.00	1.04	2.30	17.00	35.5	6.6	43.0
12	71°59.0	120°02.0	0.031	5.00	2.50	2.40	—	18.9	63.1	18.0
13	71°50.0	118°54.5	0.046	4.48	2.20	3.30	—	32.4	57.9	9.8
15	72°11.0	119°04.0	0.007	7.30	5.20	2.00	—	1.6	56.6	41.9
16	72°21.5	119°02.0	0.037	4.25	3.20	2.70	0.20	12.6	70.2	17.1
18	72°22.8	118°30.0	9.000	–3.2	30.10	5.70	0.70	7.0	32.0	60.9
19	73°12.0	115°30.0	0.034	4.80	2.30	1.60	0.40	14.2	64.3	21.1
20T	73°11.5	115°35.0	0.028	5.15	—	2.70	—	8.1	66.4	25.5
20B	73°11.5	115°35.0	0.041	4.70	1.80	1.65	0.70	54.4	32.4	12.5
21T	72°20.0	118°35.0	0.023	5.40	3.60	2.60	—	7.9	65.7	26.4
21B	72°20.0	118°35.0	0.029	5.10	2.50	1.60	0.20	48.9	38.2	12.6
22T	73°23.0	118°42.0	0.008	7.00	4.60	2.60	—	2.0	60.2	37.7
22B	73°23.0	118°42.0	0.020	5.65	2.40	1.80	0.2	36.9	52.7	10.2
23T	72°20.5	119°01.0	0.021	5.50	3.40	2.60	—	9.9	64.6	24.5
23B	72°20.5	119°01.0	0.043	4.60	2.01	1.60	0.2	61.2	31.7	6.9
24T	72°53.0	117°13.0	0.049	4.30	2.90	4.50	10.3	28.0	46.0	15.8
24B	72°53.0	117°13.0	0.079	3.90	8.60	—	26.1	55.8	13.3	4.8
25T	72°34.0	118°11.0	0.024	5.30	5.50	3.10	0.1	19.4	50.7	29.8
25B	72°34.0	118°11.0	0.053	4.25	1.60	1.25	0.3	68.6	24.7	6.4
25a	—	—	1.500	–0.5	8.70	1.60	54.5	28.4	14.2	2.9
26T	72°38.8	118°38.0	0.009	6.80	4.70	2.70	—	21.8	59.4	18.9
26B	72°38.8	118°38.0	0.035	4.80	1.30	1.00	—	75.5	13.7	10.9
27T	72°40.8	118°51.0	0.014	6.10	3.90	2.60	0.3	2.2	64.9	32.7
27B	72°40.8	118°51.0	0.020	5.70	2.10	1.25	—	36.3	52.8	10.9
28T	72°20.0	118°28.0	0.025	3.30	2.45	1.95	—	7.9	73.7	18.4
28B	72°20.0	118°28.0	0.033	4.90	1.70	1.45	0.9	51.1	37.5	10.5
29T	72°23.0	118°55.0	0.004	9.00	6.50	1.60	0.5	1.7	35.6	62.1
30T	72°22.5	119°15.0	0.023	5.45	3.40	2.80	—	8.3	66.8	24.9
30B	72°22.5	119°15.0	0.041	4.70	1.50	1.20	0.1	59.1	30.9	10.0
31T	71°56.2	120°05.0	0.007	7.10	4.50	3.00	—	3.6	65.4	31.0
32T	71°53.2	119°40.0	0.0056	7.50	3.90	2.30	—	4.7	51.8	43.6

* T = top of sample
B = bottom of sample
a = adjacent sample

TABLE I (continued)

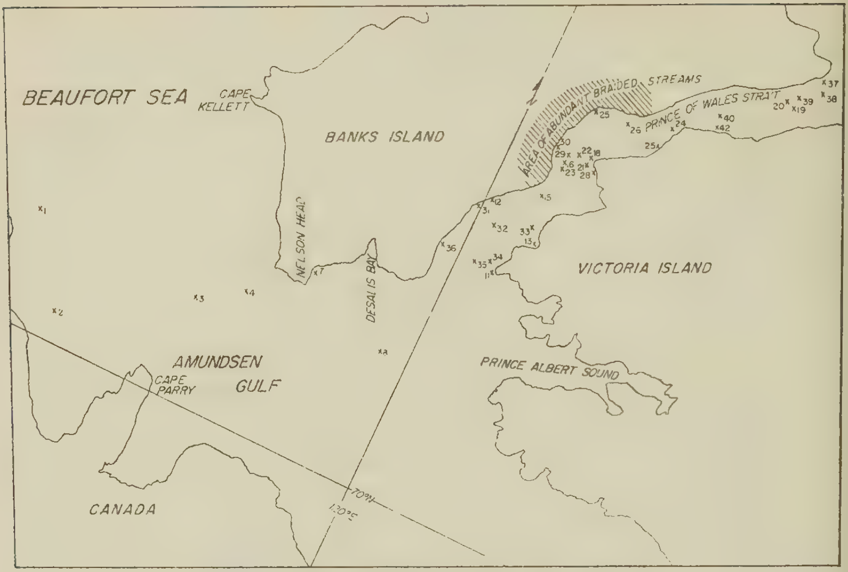
*Sample**	*Location*		*Median Diam.*		*Sorting*		*Percent*			
No.	*Lat. North*	*Long. West*	*mm*	*Ø*	*Trask*	*Ø*	*Gravel*	*Sand*	*Silt*	*Clay*
32B	71°53.2	119°40.0	0.0063	6.85	3.20	2.20	0.1	24.9	58.1	16.9
33T	71°54.6	119°05.0	0.052	4.23	1.50	1.35	—	25.9	61.9	12.2
34T	71°37.0	119°15.0	0.230	2.10	6.70	2.70	6.8	38.7	32.7	21.8
34aB	71°37.0	119°15.0	0.125	3.00	5.50	11.50	1.5	48.4	11.5	38.6
35T	71°31.0	119°46.0	0.013	6.20	3.60	32.55	—	13.4	56.5	30.1
35B	71°31.0	119°46.0	0.026	5.30	3.30	3.00	14.3	44.6	43.9	5.2
36T	71°32.3	120°27.0	0.0114	6.40	3.70	1.60	—	7.6	61.7	30.7
37T	73°23.8	115°05.0	0.033	4.90	3.40	3.05	0.1	23.2	76.8	7.8
38T	73°20.6	115°03.0	0.037	4.75	1.80	2.50	0.8	9.8	69.6	19.8
39T	73°14.2	115°30.0	0.017	5.85	1.00	2.85	0.4	3.8	73.2	22.6
39B	73°14.2	115°30.0	0.037	4.83	2.30	1.70	—	55.1	35.1	9.8
40T	73°05.0	116°38.0	0.0135	6.15	3.60	2.60	0.1	8.0	61.5	30.5
40B	73°05.0	116°38.0	0.026	5.30	2.60	2.10	0.2	45.1	40.8	13.9
42T	73°01.0	116°28.0	0.056	4.15	3.40	4.65	13.1	32.9	40.2	13.8
42B	73°01.0	116°28.0	0.047	4.45	1.08	1.30	—	82.0	5.3	12.7
Ice Island			0.052	4.60	1.60	2.00	0.3	26.3	65.6	7.9
Ice Island			0.040	4.70	1.50	1.35	0.2	68.0	31.3	3.3

* T = top of sample
B = bottom of sample
a = adjacent sample

portion, making a total of 52 mechanical analyses. In addition, two samples from the ice island were analyzed. Table I and Fig. 2 give the location of all samples and their sedimentary parameters.

Size Distribution. The size parameters considered in this paper are: (1) median diameter, (2) modal diameter, (3) sorting, and (4) percent gravel, sand, silt, and clay. Many of the samples are bimodal, thus the median diameter may not always represent a good view of the size distribution. In some cases the median may fall in an area between the two modes where the actual percentage of that specific size is low. Also, it is difficult at times to consider a sorting factor when two modes are present. If the two modes fall between the 25 and 75 percentile (16 and 18 percentiles for Ø sorting) it is possible to have a sorting value which indicates good sorting. These difficulties invariably arise when using such parameters to describe a sedimentary deposit.

MEDIAN DIAMETER: This was calculated for all of the samples. In describing the sediments by this parameter it was found that


BEAUFORT SEA
CAPE KELLETT
BANKS ISLAND
NELSON HEAD
DESALIS BAY
AMUNDSEN GULF
CAPE PARRY
CANADA
VICTORIA ISLAND
PRINCE ALBERT SOUND
PRINCE OF WALES STRAIT
AREA OF ABUNDANT BRAIDED STREAMS
N
70°N
120°E
1
2
3
4
7
8
36
31
12
15
32
33
13
35
34
11
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42
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19
39
37
38

Figure 2. Map showing location of all samples.

4 %~0~ of the medians are in the category of coarse sand and larger, 4 %~0~ in both medium and fine sand ranges, 37 %~0~ in the coarse silt range, 31 %~0~ in the medium silt range, and 20 %~0~ in the fine silt. There are no medians which can be classified as clay.

By means of the median diameter, all but one sample from Amundsen Gulf can be described as silt. Sample 7, taken immediately offshore from Nelson Head, is fine sand.

Sediments from Prince of Wales Strait are also primarily silt, but those on the Banks Island side are noticeably finer than those on the Victoria side. The average median diameter of the top sediments for the Banks Island side of the center line is 0.018 mm while that for the Victoria side is 0.161 mm. The bottom portions of the samples show the same characteristic; the Banks side 0.029 mm, the Victoria side 0.047 mm.

In addition to the horizontal distribution there is also an apparent vertical change in median diameter. All but one of the 14 top and bottom pairs indicate a smaller average median diameter for the surface layer (0.022 mm) than for the subsurface layer (0.035 mm).

Modality: Although most of the modes fall in the range of fine sand to coarse silt; *i. e.*, 0.062 to 0.031 mm, there are some in the gravel and clay range. About 50 % of the sediments sampled show some degree of bimodality, the other half being unimodal. The bimodals are usually either in the gravel range and fine sand or silt, or in the clay range and fine sand and silt. Fig. 3 gives some selected examples of the modal distribution.

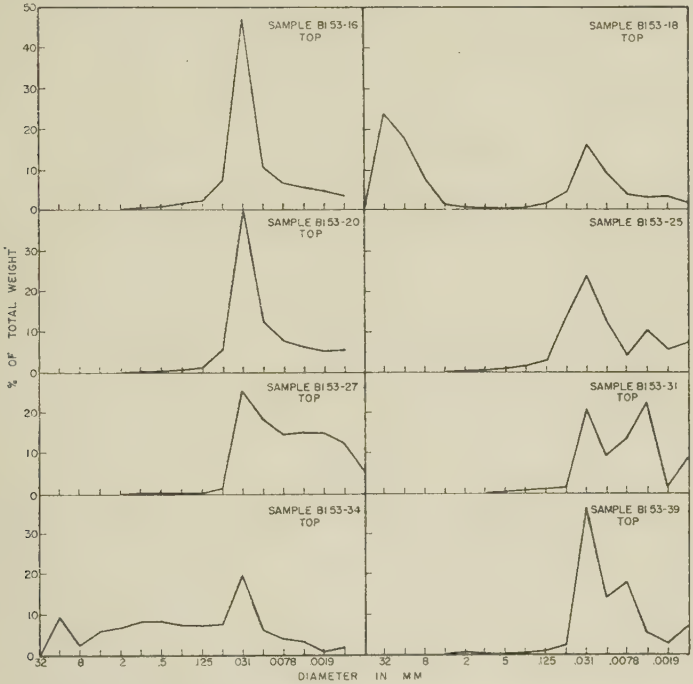

Figure 3. The modal distribution in some selected sediment samples.

It is particularly noticeable that the modes for the top samples are principally at about 0.031 mm, while those of the bottom portions are at approximately 0.062 mm. In other words, the bottom portion is consistently larger than the top part. This agrees with a similar observation with respect to the median diameter.

Sorting: According to Trask (Krumbein and Pettijohn, 1938), sediments exhibit good sorting when the value for $\sqrt{Q_3/Q_1}$ is less than 2.5, normal or fair sorting when it lies between 2.5 and 4.15, and poor sorting when it is greater than 4.5.

The sediments examined show sorting values which range from 1.0 to 30.1. Of these sediments, 37 % have good, 14 % fair, and 22 % poor sorting coefficients. Except for one sample, those from the southern third and northern third of Prince of Wales Strait have good or fair sorting while the central third have fair to poor sorting coefficients; none of the samples in the central area show good sorting.

The six samples taken in Amundsen Gulf have fair and good sorting values. Samples 1 and 7, both from shallow water, also have median diameters in the fine sand range. Samples 2, 3, 4, and 8, further from shore in deeper water, have medians in the silt range.

Gravel, Sand, Silt, and Clay: Here the term gravel is used for particles larger than 2.0 mm, sand for those from 1.0 to 0.062 mm, silt for particles from 0.062 to 0.0039 mm, clay for those finer than 0.0039 mm. The gravel component ranges from 0 to 56 % of the total sample, sand from 1.6 to 82.0 %, silt from 3.7 to 76.0 %, and clay from 2.9 to 62.0 %.

The gravels are apparently concentrated on the Victoria side. Of the 12 samples with gravel concentrations of 0.5 % or more, nine are from that side, with the remaining three along the center of the Strait. There is little if any gravel found in deposits on the Banks side.

On the average, the sand concentration is also on the Victoria side, where the samples have an average of 22 % while those near Banks Island contained an average of 11 %. In contrast, samples from the Banks side consist of 63 % silt on the average while those on the Victoria side have 48 %. Though there may be wide variations in the clay fractions of discrete samples, the average is about the same for both sides of the Strait. The Banks side contains about 29 % clay and the Victoria side about 21 %. It is quite obvious from this that the portion of the Strait adjacent to Banks Island contains the smaller sizes, principally silts, while the Victoria side contains most of the sand and gravel. This observation corresponds with the distribution indicated by the median diameter.

The coarse fraction of a sample is more concentrated in the lower portion than in the upper, for in almost all instances there is less gravel in the surface sediments (1.5 %) than in the lower sections

(3.0 %). The sand concentration is even more striking than that of the gravel, with an average of about 12 % in the top and 50 % in the bottom.

Rock and Mineral Composition. Results of microscopic examinations indicate that the sediments are principally composed of quartz, limestone, sandstone, quartzite, and basic rocks (see Table II). In addition there are other minerals as well as biological material, but in general these latter two categories comprise only a small fraction of the sample. Note, therefore, that the percentages do not include the biological and minor mineral or rock fragments. The quartz content of the deposits varies from 26 to 72 %, limestone from 11 to 46 %, sandstone and quartzite from 7 to 20 %, and basic rocks from 6 to 25 %.

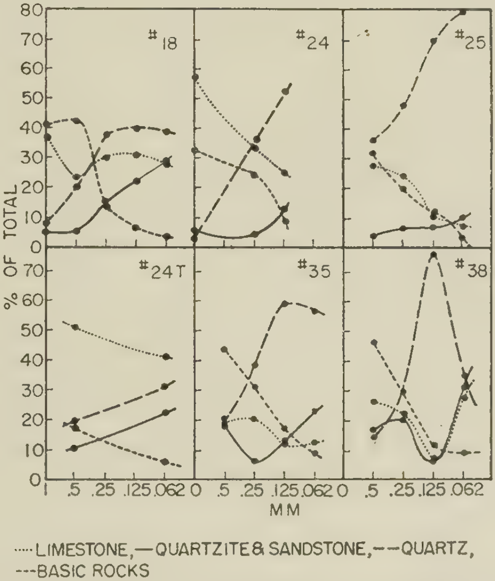

Figure 4. The rock and mineral composition of some selected sediment samples.

In keeping with the presentation of data for size distribution, Prince of Wales Strait is proportioned into two sections. Quartz comprises about 65 % of the sediments on the Banks side and 39 % on the Victoria side. Limestone is more noticeable in the area near Victoria Island with 24 versus 18 %. Sandstone and quartzite

TABLE II. Results of Microscopic Examination of Samples

Sample No.	*Size Fraction (mm)*	*Percent Composition*			
		Quartz	*Limestone*	*Sandstone, Quartzite*	*Basic Rocks*
8	.5	37	37	6	8
	.25	67	16	5	11
	.125	71	11	9	8
	.062	50	22	19	9
12	.25	63	19	9	9
	.125	62	12	15	11
	.062	69	8	15	8
13	.5	30	34	8	27
	.25	54	11	11	24
	.125	58	11	14	15
	.062	47	16	27	8
15	.25	64	13	8	14
	.125	75	8	8	9
	.062	71	14	10	5
16	.25	57	29	—	14
	.125	56	39	—	5
	.062	59	36	—	5
18	1.0	8	36	5	41
	.5	20	23	5	43
	.25	38	30	15	14
	.125	40	31	22	6
	.062	38	28	29	4
19	.25	42	35	7	16
	.125	68	11	8	12
	.062	43	29	24	4
20	.25	47	25	17	11
	.125	46	32	15	6
	.062	53	20	24	2
21	.25	51	26	14	7
	.125	42	16	25	16
	.062	45	26	21	8
22	.25	60	21	11	8
	.125	57	15	19	9
	.062	60	19	14	7

TABLE II (continued)

Sample No.	*Size Fraction (mm)*	*Percent Composition*			
		Quartz	*Limestone*	*Sandstone, Quartzite*	*Basic Rocks*
23	.25	53	23	12	11
	.125	50	21	17	12
	.062	63	15	12	9
24	1.0	4	57	6	33
	.5	—	Lost	—	—
	.25	37	34	4	25
	.125	52	26	13	9
25	.5	36	28	5	31
	.25	48	25	7	20
	.125	69	11	7	12
	.062	79	8	10	3
26	.25	34	16	8	11
	.125	51	11	18	14
	.062	80	5	7	8
28	.5	21	30	3	45
	.25	49	18	6	26
	.125	57	20	10	12
	.062	49	16	10	20
29	.25	73	19	8	8
	.125	39	19	10	20
	.062	43	18	17	22
30	.25	68	14	7	8
	.125	80	8	6	6
	.062	69	10	10	11
31	.25	71	8	9	12
	.125	64	11	16	9
	.062	59	13	21	7
32	.25	68	17	7	8
	.125	56	21	16	7
	.062	44	28	19	8
33	.25	59	20	19	2
	.125	60	11	12	17
	.062	49	12	24	15

TABLE II (continued)

Sample No.	*Size Fraction (mm)*	*Percent Composition*			
		Quartz	*Limestone*	*Sandstone, Quartzite*	*Basic Rocks*
34A	1.0	4	34	10	36
	.5	27	43	13	8
	.25	38	9	28	19
	.125	43	10	26	20
	.062	48	17	25	10
35	.5	20	19	18	43
	.25	38	20	6	31
	.125	58	12	13	17
	.062	56	13	23	8
36	.25	74	12	4	9
	.125	80	8	7	5
	.062	60	16	13	11
37	.5	13	42	—	45
	.25	46	32	—	21
	.125	60	7	4	29
	.062	39	57	—	4
38	.5	14	25	16	45
	.25	29	22	20	29
	.125	75	7	6	11
	.062	34	27	30	9
40	.25	55	13	6	26
	.125	22	22	14	22
	.062	47	28	14	11
42	1.0	1	57	6	36
	.5	21	36	28	13
	.25	42	15	4	32
	.125	40	17	10	32
	.062	57	18	17	6

appears to have about the same average distribution, with 11 and 13 $^0/_0$ respectively on the Banks and Victoria sides. The basic rocks show some differentiation in that there is an approximate 10 $^0/_0$ average for the Banks Island portion and a 20 $^0/_0$ average for the Victoria Island side.

In considering the various size fractions for the quartz content, note that in general quartz is relatively low in the coarse sand and more abundant in the fine sand. In some instances, however, it appears to be equally abundant in all size fractions, although it may drop in concentration in the fine sizes. Sandstone and quartzite often show a decrease in the fine sand sizes. Generally limestone shows a decrease in concentration as the particle size becomes smaller, and the basic rocks show a definite decrease in concentration in the smaller size fractions. Fig. 4 shows a set of selected plots of the percent composition of the various rocks and mineral components.

CONCLUSION

The sediments of Amundsen Gulf and Prince of Wales Strait appear to be principally silts mixed with varying amounts of gravels, sands, and clays. Although some of the samples indicate a predominance of sands and gravels, these may have been rafted into the area by sea ice.

The bimodality shown by about half of the samples may be the result of "dumping" of sediments that have been accumulated in or on the ice; as it melts the ice deposits the coarse sediments in an area where only fine material would usually be deposited by normal means while the fine sediment released from the ice is probably subjected to the current regime of the area.

The most probable explanation of the fair to poor sorting of sediments from the central portion of Prince of Wales Strait lies in the disposition of fine material carried by the relatively large number of streams which drain into this area from Banks Island. All of the poorly sorted samples are relatively high in silt and clay content.

The noticeable coarseness of deposits adjacent to Victoria Island in comparison with those near Banks Island may be due in part at least to currents winnowing out the fine constituents. However, current data are exceedingly sparse and not available at this time. Also it is possible that ice does much of its melting in place on the Victoria side so that any coarse ice-rafted load would then be deposited there.

The bottom portion of sediment samples was almost invariably coarser than the portion at the very surface. It is difficult to postulate a very recent change in the depositional environment as there is no additional evidence to support this contention. However, when one considers the fluidity of surface sediments versus that of deeper deposits then it is quite possible that the coarse material has been incorporated into the previously deposited sediments by the action of currents or by settling. This is an important consideration in any sedimentary investigation. If such were the case then observations concerning deposits are not necessarily in accord with the time factor involved in the deposition of the particles.

The minerals and rocks appear to be derived dominantly from sedimentary and basic igneous rocks, which is in contrast to sediments from the Beaufort and Chukchi seas. The quartz content of sediments in Amundsen Gulf and Prince of Wales Strait may have come from sedimentary or acid igneous rocks.

The decrease in basic igneous rocks with particle size is quite normal and should be expected, since these rocks and their associated minerals generally would be less resistant to weathering than would the quartz fraction. Likewise the limestone, which is detrital in nature, should decrease in concentration with decreasing size. On the other hand, sandstone, quartzite, and quartz, being more resistant to weathering, should normally show a relative increase in concentration with a decrease in size.

The predominance of basic igneous rocks adjacent to Victoria Island may be explained by two lines of reasoning. Possibly there is a greater supply of basic material on the Strait shore of Victoria Island than on the Banks shore. But it is also quite possible that the ice which holds the basic rocks as well as other materials melts in place more profusely along the Victoria shore than along the Banks shore. Thus ice adjacent to Banks Island may well be carried away by currents. This latter possibility accords better with our observations than the former possibility.

Ice on the sea surface makes this or any other region a complex area to study. Though wave or tidal action is relatively negligible, the presence of the ice in itself increases the complexity of the situation. While sedimentation occurs in what might be considered more normal ways in most other marine areas of the world, it is greatly modified in Arctic regions due to ice-rafting. As a case in point, we may note the ice islands observed in Prince of Wales Strait. Presumably these originated from the shelf ice at Ellesmere Island over 1000 miles away and evidently drifted in from the vast permanent Arctic ice pack to become grounded in the Strait.

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SPRING CHANGES IN PHYTOPLANKTON ABUNDANCE IN A DEEP ESTUARY, HOOD CANAL, WASHINGTON[1]

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ABSTRACT

Spring changes in abundance of plankton pigments (Jan.–May, 1953) in Hood Canal, a deep estuary on the coast of the State of Washington, are described. Since there was a less dense brackish surface layer throughout the period of observation, these changes in plankton abundance are not a result of changes in the stability of the water column such as those that initiate spring flowering in temperate coastal waters. Rather, they appear to have been brought about by seasonal changes in solar radiation and transparency which caused marked differences in the depth of the euphotic zone and in the mean illumination in the mixed surface layer. As a result there were great seasonal changes in the rate of photosynthesis of the population in the mixed surface layer with which the general changes in phytoplankton abundance were related.

INTRODUCTION

The spring diatom flowering in temperate waters offers an outstanding illustration of the significance of a stable water column for the development of abundant phytoplankton populations. In positive estuaries, stability is almost wholly a result of dilution rather than warming. Since the occurrence and characteristics of a stable surface layer in deep estuaries will depend much more on seasonal changes in salinity than on temperature, we may anticipate some distinct and interesting differences in the development of phytoplankton populations in estuaries as compared to open coastal and offshore regions. These differences are generally most apparent in the spring of the year when the populations are changing most rapidly. The purpose of the present paper is to demonstrate the significance of physical and chemical changes in the surface layer to changes in phytoplankton abundance in the spring of the year in a deep estuary, Hood Canal, Washington.

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METHODS

Hood Canal is one of the deep natural channels in the Washington coastline (Fig. 1). From its connection with Admiralty Inlet in the north to its southern extremity the entire canal is about 50 miles long. However, this study is concerned principally with the 30-mile portion south from Quatsap Point, south of which the Canal is nearly straight for a stretch of 20 miles, with a width of about a

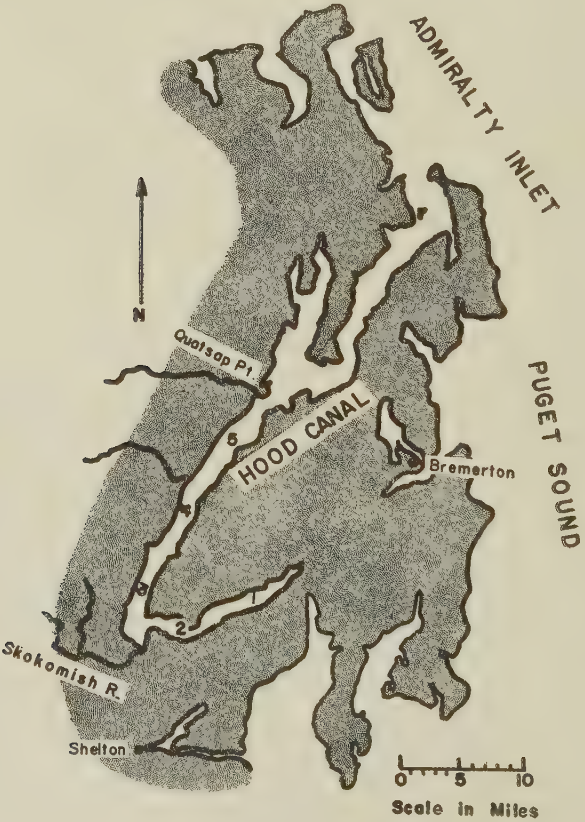

Figure 1. Hood Canal, Washington. Numbers indicate locations of stations.

mile and uniform depths of 75–90 m. As it bends abruptly to the east it begins to shoal, reaching depths of 5 or 6 m in the last two or three miles.

This southern half of the Canal receives fresh water from a number of rivers and small streams draining the surrounding mountainous country. The largest of these is the Skokomish River (drainage area, 230 mi²) which originates at elevations of 4,600 to 5,000 ft. in the western Olympic Mountains and empties into the southwestern angle of the Canal. Two other rather large streams enter the Canal's western shores: the Duckabush (drainage area, 65 mi²) at a point three miles north of St. 5 and the Hamma Hamma (drainage area, 50 mi²) about three miles south of St. 5. The remainder of the fresh water enters through a number of smaller streams along both shores and by direct runoff.

During the period of this study, the Water Resources Division of the U. S. Department of the Interior maintained gages on five of the rivers in this area: the Union, Tahuya, Skokomish, Dewatto and Hamma Hamma, accounting for about 68 % of the total drainage area of around 620 mi². Total stream flow into the Canal below Quatsap Point was estimated by dividing the drainage area of that part of the Canal (as determined from U. S. Geological Survey topographic maps) into four sections, each containing one or more gaged streams. The areas in each section drained by ungaged and gaged streams were determined with a planimeter, and the total drainage was estimated from the stream flow records and from the proportion of gaged to ungaged areas. No attempt was made to account for direct runoff or seepage.

Daily solar radiation measured at the Seattle-Tacoma airport about 30 miles east of the Canal has been published in U. S. Weather Bureau Climatological Summaries. This Weather Bureau Office has also provided unpublished hourly radiation measurements for each sampling day.

Observations were made during regular monthly hydrographic surveys of Puget Sound by the R. V. Brown Bear, operated by the Department of Oceanography, University of Washington. After a preliminary study in November 1952, surveys were made January 22, February 18–19, March 17–18, April 17–18 and May 20–21, 1953. Phytoplankton, salinity, temperature and transparency were measured at a number of stations along the entire north-south axis of the Canal, including the five that were regularly occupied in the southern portion, as indicated in Fig. 1. Salinity and temperature were sampled with Nansen bottles and reversing thermometers at standard depths from surface to bottom. Separate casts with 2.5 liter Atlas bottles sampled the phytoplankton at from four to six depths in the upper 50 to 75 m, with four samples usually being taken in the upper 25 m. From 25 to 40 phytoplankton samples were taken on each of the 1953 cruises.

Salinity was determined by titration with silver nitrate. The mean salinity in various sections of the region was estimated with a planimeter from plots of the vertical distribution of salinity. The fraction of fresh water in each section was estimated (Ketchum, *et al.*, 1951) by assuming that fresh water had mixed with sea water of the maximum salinity found in the region during each cruise. This base salinity varied from 30.80 to 31.87 $^0/_{00}$. Total fresh water was estimated from this fraction and from the total volume of each section as determined from bathymetric charts (U.S.C. & G.S. # 6450 and # 6460) of the region. The flushing time in days was determined by summing cumulatively the daily total river flow preceding each survey until it equaled the total accumulated fresh water.

Phytoplankton abundance was estimated from one or two liter samples concentrated with a Foerst continuous centrifuge. After drying, pigments were extracted with 90 $^0/_0$ acetone and stored in the dark in a freezing locker until the ship returned to Seattle. Concentrations of chlorophyll *a* were then determined spectrophotometrically with a Beckman DU Spectrophotometer after the method of Richards with Thompson (1952). Mean concentrations of chlorophyll *a*, determined with a planimeter from plots of the vertical distribution, were weighted according to the volume of each section.

Samples for phosphate determinations were taken at standard depths during the April and May cruises. Soon after collecting, determinations of inorganic phosphate were made by the colorimetric method of Robinson and Thompson (1948).

Transparency was measured from January through April with a hydrophotometer in which an unfiltered photocell was exposed to an incandescent light source through a fixed light path. This instrument was unavailable for the May cruise, when transparency had to be determined by the Secchi disc. Secchi disc depths (D) were converted to extinction coefficients (k) by the relation $k = 1.7/D$ (Poole and Atkins, 1929).

RESULTS

SEASONAL CHANGE IN PHYTOPLANKTON ABUNDANCE

The principal features of the seasonal changes in abundance as indicated by chlorophyll *a* concentrations are shown in Fig. 2. The low abundance that had been observed in the preliminary survey in November continued in January when the weighted mean concentration in the upper 20 m was about 0.5 mg/m³. A slight increase in February, confined to a thin surface layer in the southern end, brought the mean to 1.1 mg/m³. By March, however, there had been a general increase to maximum values of over 10 mg/m³, resulting in a mean concentration of 8.8 mg/m³ in the upper 20 m. In April, abundance was reduced to less than a quarter of that in the previous month, with the mean concentration falling to 1.9 mg/m³. Subsequently the population again increased throughout the surveyed region and attained a mean concentration of 18.8 mg/m³.

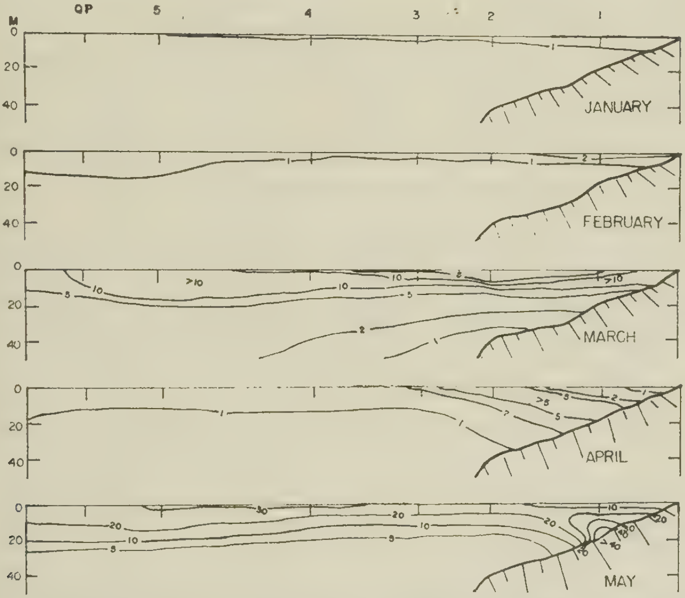

Figure 2. Vertical distribution of Chlorophyll *a* (mg/m³) in upper 50 m. Depth in meters. Numbers on abscissa indicate stations; QP = Quatsap Point.

The most striking feature of these seasonal changes is certainly the decrease in population between March and April. This decrease was much greater in the region from Skokomish River seaward than in the region east of this River (Sts. 1 and 2).

Seasonal Changes in Environmental Factors

Salinity. Fig. 3 shows that there was always a mixed brackish surface layer which varied in depth from about 5 to 20 m. Below this layer the salinities were so much higher that nearly all of the fresh water was evidently confined to this upper layer. The maximum amount of fresh water was observed in the mid-February survey (Table I), some three weeks after the peak river flow of the year. Although runoff decreased from 36 × 10^6 to 7 × 10^6 m^3/day during the month of February, the fresh water had not yet fallen much by March 17. The continued decrease in April, despite the relatively small changes in runoff, evidently represents a continuing adjustment to the larger change in runoff that took place earlier. Thus, during the first four months there was a rapid increase in

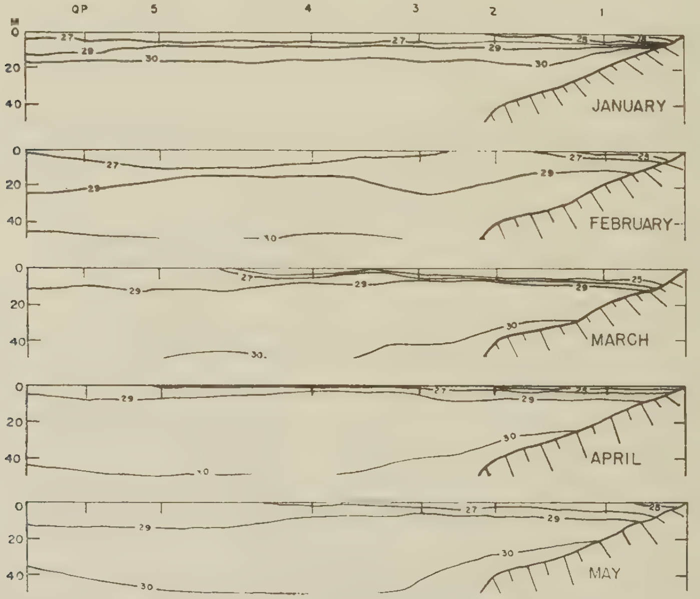

Figure 3. Vertical distribution of salinity ($^0/_{00}$) in upper 50 m. Depth in meters. Numbers on abscissa indicate stations; QP = Quatsap Point.

TABLE I. Salinity, River Flow, and Flushing Time in Upper 20 m of Hood Canal, Washington in 1953, and Solar Radiation taken at Seattle-Tacoma Airport by U.S. Weather Bureau Office

Date	*Wgtd. Mean Salinity* $(^0/_{00})$	*Aver. River Flow for Preceeding 30 Days* $(10^6 m^3/day)$	*Accumulated Fresh Water* $(10^6 m^3)$	*Flushing Time, Days River Flow Accumulated*	*Mean S.R. of Week Preceeding (g cal/cm*^{2}*/day)*	*S.R. for Day of Observations (g cal/cm*^{2}*/day)*
January 21–22	28.31	27	525	15	34	42
February 18–19	27.24	23	700	30	113	144
March 17–18	28.56	9	610	46	231	322
April 17–18	28.83	7	390	59	347	407
May 20–21	28.47	9	440	67	374	455

flushing time. Between the April and May observations there was an increase in accumulated fresh water which resulted in another somewhat smaller increase in flushing time.

In contrast to the surface layer, the deep water changed so little in salinity from February through May that the fresh water content is considered to have been practically constant. Examination of temperature-salinity relations in various parts of the Canal indicates that small decreases in salinity of the bottom water were due to intrusion of colder and more dilute water from the north.

Temperature. The temperature of the surface water varied from a minimum of about 8° C in January to a maximum of about 12.5° C in May while the deeper water showed some small decreases in the same period. These seasonal changes in temperature were so small when compared to the seasonal changes in radiation and transparency that it seems unlikely that they could have had important effects on the seasonal changes in growth and photosynthesis of the phytoplankton. They will not, therefore, be considered further.

Phosphate. At the time of the April cruise, inorganic phosphate was everywhere greater than 1.0 μg-at/l, except at the surface at Sts. 1, 2 and 3, where minimum values of 0.7 to 0.9 may be accounted for on the basis of dilution with nutrient-poor river water. In May, at the time of maximum observed populations, there was some evidence of increasing nutrient depletion above 5 m, but even then the minimum phosphate values were mostly above 0.4 μg-at/l.

Radiation and Transparency. Weekly mean solar radiation is shown in Fig. 4. Since radiation on the principal sampling day of each survey did not differ markedly from mean daily radiation in the week preceding (Table I), radiation measurements on those days have been taken to represent both total radiation and hourly changes in radiation to which the phytoplankton had been exposed in the period immediately preceding each sampling.

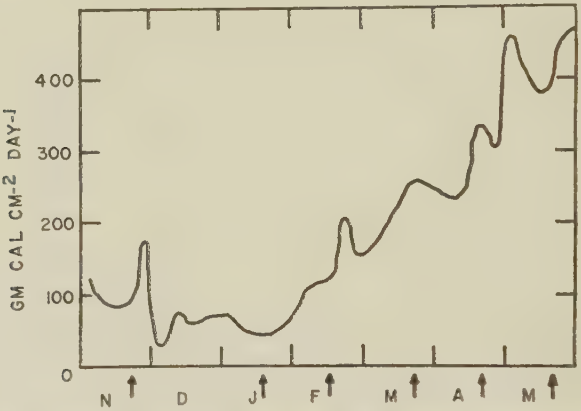

Figure 4. Solar radiation, November 1952–May 1953. Weekly means at Seattle-Tacoma Airport. Arrows indicate time of surveys.

During the first months of the year the water was exceptionally turbid, with greatest extinction coefficients at the surface in the southernmost portion (Table II). It was obvious, when sampling during periods of peak river flow in January and February, that this turbidity in the early part of the year was due to suspended matter brought in by river water. Maximum transparency occurred in April during a period of low river flow and of relatively small phytoplankton populations. It is probable that the subsequent increase in extinction coefficients in May was due to the greatly increased phytoplankton population. Riley (1956) has recently shown that in nonturbid offshore waters the relation between extinction coefficients, k, and the plant population may be given by

$$k = 0.04 + 0.0088\, C + 0.054\, C^{2/3},$$

in which C is the concentration of chlorophyll *a* in mg/m³. This relation has been used here to estimate the extinction by the phyto-

TABLE II. Extinction Coefficients and Depth of Euphotic Zone of Hood Canal, Washington. Individual Values given for Sts. 1, 3 and 5; Means include all Sts. 1–5 (see Fig. 1). Depths Based on Radiation Values in Table I. See Text for Further Explanation

Month	*Station*	*Measured Extinction Coefficient,* k_t	*Estimated Extinction by Phytoplankton,* k_p	k_p/k_t	*Depth of Euphotic Zone* (*m*)
January	1	—	—	—	1.2*
	3	1.45	0.09	0.06	2.0
	5	1.06	0.11	0.10	1.7
Mean, Sts. 1–5		*1.06*	*0.10*	*0.09*	*1.8*
February	1	2.25	0.16	0.07	1.4
	3	0.81	0.14	0.17	4.0
	5	0.39	0.10	0.25	5.0
Mean, Sts. 1–5		*1.16*	*0.14*	*0.16*	*3.5*
March	1	1.50	0.20	0.13	2.4
	3	1.08	0.16	0.15	3.4
	5	0.93	0.41	0.44	3.7
Mean, Sts. 1–5		*1.17*	*0.25*	*0.22*	*3.3*
April	1	0.36	0.16	0.44	12
	3	0.41	0.19	0.46	18
	5	0.30	0.14	0.47	16
Mean, Sts. 1–5		*0.35*	*0.18*	*0.51*	*16*
May	1	0.49	0.28	0.57	8
	3	0.68	0.41	0.60	6
	5	—	0.52	—	6**
Mean, Sts. 1–5		*0.55*	*0.41*	*0.61*	*7*

* Surface transparency from St. 3 was used to supply missing value.

** Assuming transparency to be the same as at St. 3.

plankton, k_p, from January through April at all depths for which hydrophotometer measurements of total extinction, k_t, were available. In May the approximate extinction coefficients of populations in the upper 5 m were determined. These were compared with Secchi disc measurements which gave the extinction in about the upper 5 m also. These estimated extinction coefficients are shown in Table II. It can be seen that the fraction of total extinction due to phytoplankton, k_p/k_t, increased as the phytoplankton increased in the early spring and then remained about the same in April and May.

It appears from an examination of the relation between salinity and transparency that the turbidity of incoming river water must have decreased as extinction by the phytoplankton increased. On each cruise in February, March and April there were 18 simultaneous measurements of transparency and salinity in the upper 20 m at Sts. 1–5. If it is assumed that the nonphytoplankton extinction, k_t-k_p, in a given water sample with salinity S_x is the result of simple dilution of turbid fresh water by clear ocean water, then one would expect to find a simple relation between the proportion of river water as represented by salinity and nonphytoplankton extinction. The empirical relation between extinction and salinity for these three months was found by least squares to be:

$$\begin{aligned} &\text{February,} && k_t\text{-}k_p = 4.46 - 0.147\ (S_x);\\ &\text{March,} && k_t\text{-}k_p = 4.01 - 0.129\ (S_x);\\ &\text{April,} && k_t\text{-}k_p = 0.54 - 0.015\ (S_x). \end{aligned}$$

It is obvious that no great reliance can be placed on these expressions, since transparency will certainly be affected by other processes, such as settling. However, they do give at least some indication of the magnitude of the seasonal change in the turbidity of river water, which is here estimated as having a k that is greater than 4.0 in February and March but is only 0.54 in April.

Seasonal changes in radiation and transparency, such as those outlined above, may be expected to result in marked changes in the depth of the euphotic zone. For present purposes the bottom of this zone has been set at the depth at which light is reduced to the compensation intensity observed by Jenkin (1937) in the English Channel, *i. e.*, 3 g cal/cm^2/day. The approximate depths at which this intensity occurred were determined from radiation and transparency data (see Table II). Note that in the early part of the year the euphotic zone was extremely thin; in fact, somewhat different assumptions about the compensation intensity and about the vertical variation of transparency would certainly have resulted in defining a euphotic zone that was at times only a few centimeters in depth. Nonetheless there can be little question that there were increases in the depth of this zone between January and March and that the simultaneous increase in radiation and transparency in April must have resulted in a more pronounced deepening of the euphotic zone.

he subsequent decrease in its depth in May is clearly the result of rge increases in phytoplankton.

DISCUSSION

During this survey, changes in temperature and salinity seem too mall to have had important physiological effects, and the phosphate stribution suggests that nutrient concentrations were probably too igh to have been limiting. Although no attempts have been made evaluate the standing crop of zooplankton, the general nature seasonal changes in zooplankton abundance in similar regions sewhere makes it improbable that the zooplankton could have een abundant enough in this period to have effected any notice- ble changes in the phytoplankton populations. Thus at first glance seems probable that the seasonal changes in abundance were a esponse to changes in the radiation available to the plant cells.

It has been pointed out that a brackish surface layer was always resent. This layer was so dilute that there were always relatively reat density differences between it and the underlying water; ensity differences between the surface and 20 m ranged from $\sigma_t = 1$ to d $\sigma_t = 6$. Thus density gradients were such that there must have been little effective vertical turbulent transport of phyto- lankton below the surface layer. This is borne out by the fact that hlorophyll concentrations in the deeper water remained relatively ow at all times.

Within this surface layer there were great changes in the radia- ion available to plant cells because of the combined effects of hanges in solar radiation and transparency. Riley (1957) has ointed out that the mean radiation in such a layer is given by

$$\bar{I} = \frac{I_0 (1 - e^{-\bar{k}z})}{\bar{k}z},$$

n which I_0 is the surface radiation; z, the depth of the mixed layer; nd $\bar{k}$, the mean transparency in the mixed layer. Here the depth f the mixed layer was estimated from the vertical distribution of alinity while the mean transparency was determined from plots of ransparency *vs* depth. As shown in Table III, there was little dif- erence in mean radiation between March and April, the values cattering around a mean of about 50 g cal/cm^2/day. Riley (1957) as found that in a number of temperate coastal regions a mean

TABLE III. MEAN RADIATION IN MIXED LAYER OF HOOD CANAL, WASHINGTON. INDIVIDUAL VALUES GIVEN FOR STS. 1, 3 AND 5; MEANS INCLUDE ALL STS. 1–5 (SEE FIG. 1)

Date	*Station*	*Depth of Mixed Layer (m)*	*Mean Radiation (g cal/cm²/day)*
January	1	10	4
	3	10	6
	5	10	5
Mean, Sts. 1–5		*9*	*3*
February	1	5	20
	3	5	39
	5	15	24
Mean, Sts. 1–5		*9*	*25*
March	1	5	50
	3	5	64
	5	17	26
Mean, Sts. 1–5		*8*	*52*
April	1	7	53
	3	5	64
	5	7	48
Mean, Sts. 1–5		*7*	*51*
May	1	5	169
	3	5	130
	5	12	56*
Mean, Sts. 1–5		*8*	*110*

* Assuming transparency to be the same as at St. 3.

radiation in the mixed layer of about 43 g cal/cm²/day is necessary for the initiation of vernal augmentation. This evidently represent a critical value below which photosynthesis and growth do not procee fast enough to permit rapid population growth in these regions. I is interesting to note that the mean radiation in March and Apri was close to Riley's critical value and that this was the perio when the population exhibited remarkable changes in abundance.

This great change in mean radiation in the surface layer must hav resulted in great changes in the rate of production of organic matte by the phytoplankton population. Because of differences in th vertical distribution of both phytoplankton and transparency, th quantitative nature of these changes is not immediately obvious

The effect of changes in radiation, transparency and phytoplankton distribution on rate of production was evaluated by using Ryther's (1956) investigation of the relation of photosynthesis by marine phytoplankton to light intensity.

Since neither phytoplankton nor transparency was uniform with depth, it was necessary to determine total production by estimating the production in successive meter-thick strata within the euphotic zone. It has been assumed that 50 % of the surface radiation is effective in photosynthesis (Edmondson, 1956) and that 1 g cal/cm²/day = 15,500 lux (Ryther, 1956). Mean hourly relative photosynthesis in each meter was then determined from transparency and hourly radiation data by using Ryther's (1956) diagram showing relative photosynthesis as a function of light intensity in lux. The hourly means were then summed to give the total daily relative photosynthesis of the population at that depth. Rates of production of carbon were determined from the mean chlorophyll *a* in the stratum, using the assumption that each gram of chlorophyll produced 3.7 g C/day at light saturation (Ryther and Yentsch, 1957). Results of these computations are shown in Table IV.

Comparison of the production rates in Table IV with the mean radiation in the mixed layer shown in Table III shows that it was not until mean radiation exceeded 50 g cal/cm²/day in March and April that there were marked increases in production rates. This makes quite clear the strong effect that the great turbidity of the early spring must have had on the growth of the population, for the mean radiation in the shallow mixed layer in February would have exceeded 50 g cal/cm²/day if the water had been as transparent then as it became in April. Differences in turbidity also clearly affected the rates of production of the population at the several stations; for example, compare the production in February at St. 1 ($k = 2.25$) with that at St. 3 ($k = 0.81$), or of that in March at St. 1 ($k = 1.50$) with that at St. 5 ($k = 0.93$), etc.

As a result of these changes in solar radiation, transparency and standing crop, there was an increase of more than 200 times in the rate of production per unit area in the five months studied. Note, however, that in the same time there was barely a doubling of the rate per unit of chlorophyll. Despite large changes in radiation and transparency, it appears that when the population is always confined to a relatively shallow layer, remarkably effective utilization of available light is permitted.

TABLE IV. Primary Production in Hood Canal, Washington. Individual Values given for Sts. 1, 3 and 5; Means Include all Sts., 1–5 (See Fig. 1) g C/m²/day

Date	*Station*	*Total*	*Per gram Chlorophyll*
January	1	13×10^{-3}	11×10^{-3}
	3	12	10
	5	10	9
Mean, Sts. 1–5		*12*	*9*
February	1	41	15
	3	93	17
	5	77	10
Mean, Sts. 1–5		*73*	*15*
March	1	310	15
	3	330	15
	5	830	18
Mean, Sts. 1–5		*452*	*16*
April	1	810	16
	3	480	22
	5	210	21
Mean Sts. 1–5		*686*	*20*
May	1	1,820	18
	3	2,440	19
	5	3,480*	21
Mean Sts. 1–5		*2,646*	*19*

* Assuming transparency to be the same as at St. 3.

The seasonal events considered offer no explanation for the population decrease between March and April; in fact, there seems little basis even for speculation about possible causes. All that can be suggested is that it may be in some way related to the great decrease in accumulated river water that took place between the March and April surveys. It is true that, despite this decrease there was no increase in the flushing rate, but the fact that the least population change occurred where there was no decrease in accumulated river water, *i. e.*, at Sts. 1 and 2, lends some credence to this suggestion. It any event, this unexplained population change does serve to emphasize that, in such regions, the population growth is strongly influenced by opposing effects of river flow; on the one hand the flow creates a shallow and stable surface layer which acts to retain the population in the euphotic zone whereas on the other and, at times of great runoff, it may cause such increases in the ate of seaward transport and in the turbidity of the surface layer hat the population growth is reduced. Considering the complex ature of the effect of the runoff, one may expect some such population fluctuations.

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SOME CONSIDERATIONS OF OXYGEN UTILIZATION RATES I PUGET SOUND[1]

By

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ABSTRACT

Concentrations of dissolved oxygen in tributary basins of the fjord-like Puge Sound region (Washington) have been determined during monthly surveys of wate characteristics. By selecting periods when a consideration of conservative propertie suggests that the effects of advection and diffusion are small, the local rates of chang in oxygen concentration have been determined; it is assumed that these rate approximate the utilization or consumption rates. These rates, which average 5.8 ml/l/yr, were somewhat higher in shallow basins than in deep basins, decrease with increase in time after the water entered the basin, and were considerabl higher than values that have been reported for oceanic waters.

INTRODUCTION

The concentration of dissolved oxygen in marine waters has lon been of concern to oceanographers and fisheries biologists. Mor recently, with expanding waterfront populations and increase discharge of domestic and industrial wastes into coastal waters sanitary engineers and others concerned with pollution problem have been paying increasing attention to the concentration of dissolved oxygen in inshore waters. Of all the nonconservative variable in the sea, the distribution of dissolved oxygen is perhaps the bes documented because it is routinely determined on most oceanographi surveys. Richards (1957) has recently reviewed the subject of dissolved oxygen in the ocean. Despite the rather widespread knowledge of oxygen distribution, the rate at which oxygen is used *i* *situ* remains an open question, with various authors quoting quit different rates for ocean waters. Measurements using the rate o hange of oxygen concentration in water contained in small bottles re open to the criticism that an impounded sample behaves dif- erently from that *in situ* (Zobell and Anderson, 1936; Rakestraw, 947).

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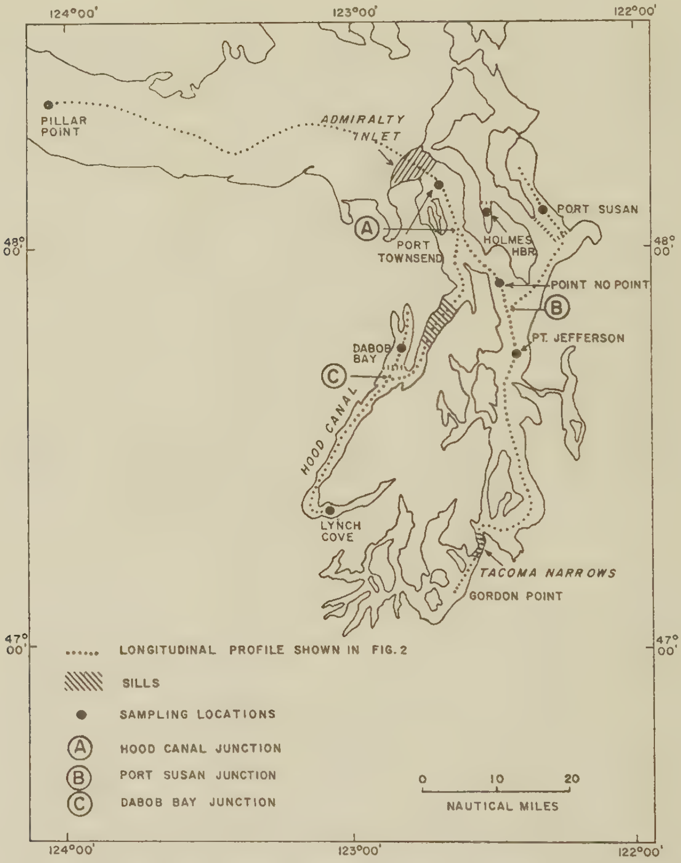
In the photic zone of the sea the oxygen concentration tends to e altered by local production, diffusion and advection, exchange oxygen across the sea surface, and biochemical utilization. Too ttle is known of these individual processes to use the oxygen con- entration or its change with time as a basis on which to estimate xygen utilization rates. Below the photic level the situation is newhat less complex, a steady state implying a balance between he processes of diffusion and advection on the one hand and util- ation on the other. If natural situations can be selected wherein he effects of diffusion and advection are negligible compared to the ate of utilization, the local rate of change in oxygen concentration hould then indicate the rate of oxygen utilization.

Certain of the fjord-type regions, such as Puget Sound, provide atural situations in which relatively dense water is at times en- rapped behind sills in deep basins or in certain appendages. This water may remain there for periods varying from a few months to more than a year, during which time the overlying water is somewhat less dense than that below sill depth. During these periods he concentration of dissolved oxygen at depth in the basins gradually decreases, then suddenly increases when the basin water is replaced by water of greater density that flows in over the sill. In general, the most active period of replenishment throughout most of the Puget Sound system occurs in late summer or fall following the subsurface intrusion of relatively low-temperature, high-salinity water into the Strait of Juan de Fuca from the Pacific Ocean. This water is associated with upwelling and is usually present in maximum amount in August (University of Washington, 1953).

In their discussion of fjords in British Columbia, Thompson and Barkey (1938) called attention to the low concentrations of dissolved oxygen in embayed waters tributary to the Northeast Pacific Ocean; hey suggested a mechanism by which water, partially depleted of oxygen when it is in contact with the bottom, might later appear at an intermediate depth to provide a zone of minimum oxygen. Additional data (largely unpublished) collected by Thompson with his coworkers and students also showed relatively low concentrations of dissolved oxygen in the deep waters of certain partially isolated basins of the Puget Sound system. Oxygen utilization rates were not determined. In the present study an attempt has been made to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PT. JEFFERSON
DABOB BAY
HOOD CANAL
LYNCH COVE
TACOMA NARROWS
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A
B
C
LONGITUDINAL PROFILE SHOWN IN FIG. 2
SILLS
SAMPLING LOCATIONS
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Figure 1. Plan view of Puget Sound showing sills and selected sampling locations.

determine oxygen utilization rates by using selected observations obtained from certain tributary basins in the Puget Sound area a periods of time when advection and diffusion of basin waters ap peared to be minimal and during which periods dissolved oxygen concentrations decreased progressively with time.

SAMPLING LOCATIONS AND OBSERVATIONS

Fig. 1 shows the principal sills and selected sampling locations n Puget Sound. Fig. 2 is a schematic longitudinal profile of the uget Sound basin and selected appendages. The sampling was one at monthly intervals during 1953 and 1954. No attempt was ade to determine the microstructure of the water behind the sills r to measure short-period changes in concentration, although re- ent unpublished data[2] for Dabob Bay show the existence of oxy- en microstructure which is apparently associated with a complex hermal microstructure described for this Bay by Shaw and Garri- n (1959). Fig. 3 shows local dissolved oxygen concentrations during 953 and 1954 for representative basin waters during rather extended ntervals of time when circulation at depth in the selected locations as considerably restricted. Table I gives the concentrations of dis- olved oxygen and the associated values of temperature, salinity, nd density. The Winkler method, as modified by Thompson and Robinson (1939), was used to determine the dissolved oxygen con- ent. Conventional oceanographic methods were employed to deter- mine temperature and salinity. The situations prevailing in three lifferent subdivisions of Puget Sound are as follows:

Dabob Bay. This was judged to be the location least affected by dvection and diffusion. The selected sampling depth of 180 m was about 50 m below sill depth and as much as 10 m off the bot- om, depending on the tide stage and displacement from the selected station position. According to Gran and Thompson (1930), the compensation depth for nearby waters varies from 10 to 18 m, thus photosynthetic processes are presumably negligible in the deep waters of this Bay. Vertical gradients of temperature and salinity t 180 m usually were less than 0.05° C and 0.05 $^0/_{00}$ per 10 m. The drifts in temperature and salinity were 0.1° C and 0.2 $^0/_{00}$ respectively during the 8-month period from January 22 to September 22, 1953, when the oxygen concentration dropped from 4.03 to 1.08 ml/l. This corresponds to a local rate of change in oxygen of 0.012 ml/l/day. In general, below sill-depth the spatial gradients of oxygen concen- tration were small, changes apparently being more of a function of ime than of space. While the decrease in oxygen concentration continued between September and October 1953 at a reduced rate

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[2] University of Washington Department of Oceanography, Brown Bear Cruise 221, March 3–5, 1959.

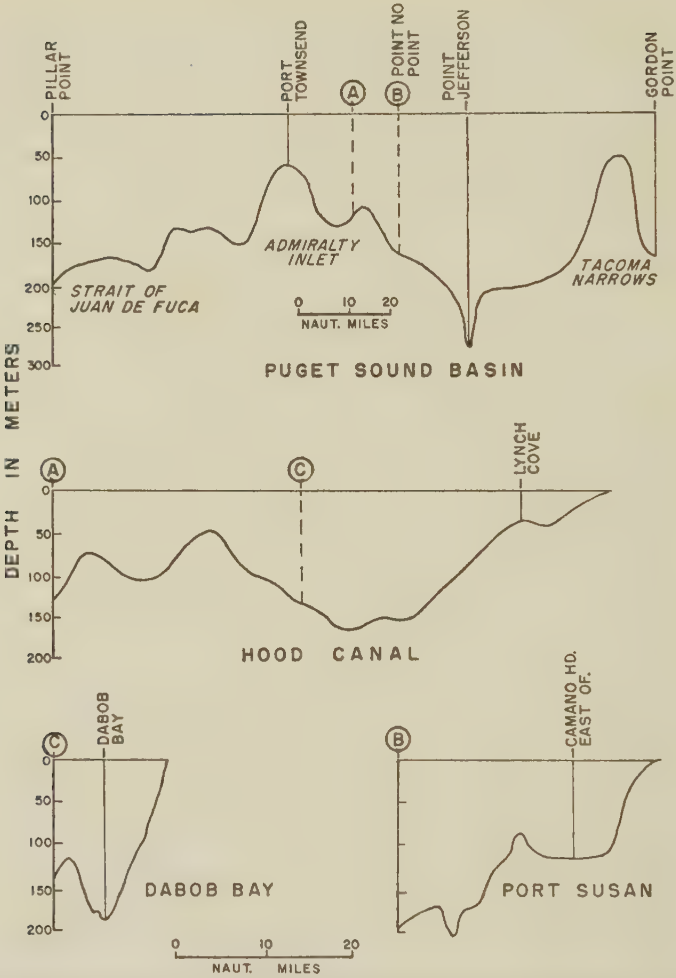

Figure 2. Schematic longitudinal section of the Puget Sound basin and selected appendages.

compared to previous months, a relatively larger change occurred in both temperature and salinity, suggesting an increased effect of advection and diffusion (see Table I). From June to September 1953 the density of the available water entering over the entrance sill to Hood Canal and Dabob Bay increased rapidly, but the density at the sill did not reach that of the bottom waters in Dabob Bay. A small amount of denser water probably passed over the sill in

October 1953, for water of relatively high oxygen concentration was found that month at the very bottom of Dabob Bay (193 m); however, it was found at only one location and not at intermediate levels below sill depth. Apparently this denser water was missed because measurements on the sill that month were made near the end of an ebb tide when the lowest density water of a particular tidal cycle is usually found. Moreover, denser water occurring in the entrance channel during certain periods within a month could easily be missed on monthly sampling cruises. The flushing which began in October 1953 stopped in its early stages, most likely as a result of heavy rainfall and runoff which decreased the density of the mixed water that flowed across the sill. After December 1953 the water characteristics fluctuated somewhat erratically until the period of March to June 1954 (see Table I). During this latter period the temperature and salinity changed but slightly while the concentration of dissolved oxygen decreased at approximately 0.010 ml/l/day, a slightly lower rate than that during the period January to September 1953.

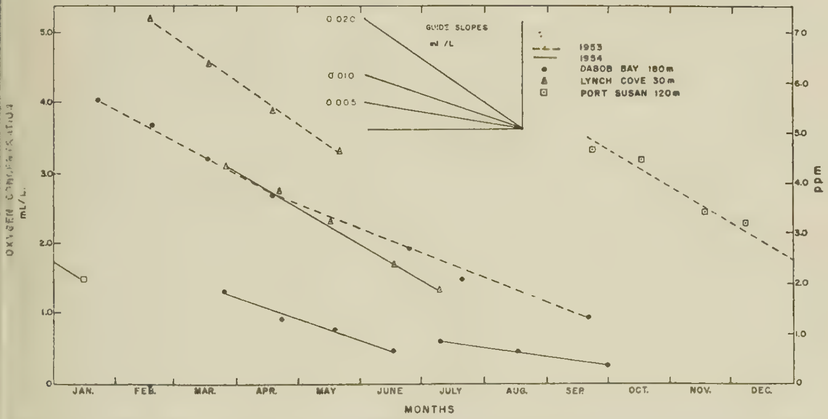

Figure 3. Dissolved oxygen concentrations in Puget Sound sub-basins. (Parts per million, ppm, are expressed on a weight basis, using an average density of 1.023 for basin waters.) Guide slopes should read ml/l/day.

In June 1954 the density at sill depth increased so that it was slightly above that at basin depths (σ_t 23.46 as compared to 23.43), and some new water penetrated into the bottom of the Bay. The density of the water at the sill decreased again between June and

TABLE I. WATER PROPERTIES IN PUGET SOUND BASINS

DABOB BAY (at 180 m) Lat. 47°44.8′ N Long. 122°49.8′ W
(Sill Depth, Entrance to Hood Canal, 50 m; Hood Canal to Dabob Bay, 130 m; Maximum Depth, 190 m)

Date	*Temp.* (° *C*)	*Salinity* (⁰/₀₀)	σ_t (*g/l*)	*Oxygen* (*ml/l*)
1953				
22 January	8.94	30.99	24.02	4.03
18 February	8.88	31.00	24.03	3.67
17 March	8.93	30.95	23.99	3.19
18 April	8.91	30.96	24.00	2.71
24 June	8.84	30.90	23.96	1.94
20 July	8.85	30.83	23.90	1.49
21 August	8.81	30.81	23.90	1.44
22 September	8.84	30.79	23.87	1.08

Average rate of oxygen utilization from 22 January to 22 September = 0.012 ml/l/day

24 October	8.87	30.73	23.82	0.86
16 November	8.80	30.71	23.81	1.14
9 December	9.09	30.65	23.73	1.14
1954				
15 January	9.45	30.64	23.66	1.48
19 February	9.66	30.58	23.58	1.37
25 March	9.76	30.59	23.57	1.32
22 April	9.78	30.52	23.52	0.91
18 May	9.75	30.48	23.51	0.76
17 June	9.74	30.41	23.43	0.45

Average rate of oxygen utilization from 25 March to 17 June = 0.010 ml/l/day

9 July	9.60	30.36	23.42	0.63
17 August	9.55	30.30	23.39	0.46
30 September	9.56	30.27	23.37	0.24

Average rate of oxygen utilization from 9 July to 30 September = 0.005 ml/l/day

17 November	9.74	30.36	23.39	3.71

PORT SUSAN (at 120 m) Lat. 48°04.0′ N Long. 122°19.7′ W; (Sill Depth, 100 m; Maximum Depth, 125 m)

Date	*Temp.* (° C)	*Salinity* (⁰/₀₀)	σ_t (*g/l*)	*Oxygen* (*ml/l*)
1953				
23 September	11.14	30.56	23.32	3.36
16 October	11.19	30.65	23.38	3.20
17 November	11.14	30.62	23.37	2.45
7 December	11.10	30.62	23.36	2.31

Date	Temp. (° C)	Salinity ($^0/_{00}$)	σ_t (g/l)	Oxygen (ml/l)
1954				
12 January	11.10	30.53	23.31	1.47

verage rate of oxygen utilization from 23 September 1953 to 12 January 1954 = 017 ml/l/day

16 February	10.80	30.25	23.14	1.14
23 March	10.08	29.87	22.96	1.70
19 April	8.08	29.34	22.84	4.69

YNCH COVE (at 30 m) Lat. 47°21.5′ N Long. 123°03.8′ W
(Sill Depth, 35 m; Maximum Depth, 50 m)

Date	Temp. (° C)	Salinity ($^0/_{00}$)	σ_t (g/l)	Oxygen (ml/l)
1953				
18 February	8.37	29.52	22.88	5.18
18 March	8.56	30.00	23.30	4.56
18 April	8.62	29.99	23.29	3.86
21 May	8.61	29.97	23.28	3.29

Average rate of oxygen utilization from 18 February to 21 May = 0.020 ml/l/day

25 June	8.90	29.74	23.05	2.07
20 July	9.17	29.76	23.02	1.70
21 August	9.40	29.73	22.96	1.51
22 September	8.94	29.95	23.20	1.31
23 October	9.24	30.18	23.35	1.43
17 November	9.44	30.26	23.38	1.43
9 December	9.64	30.20	23.29	1.23
1954				
15 January	9.73	29.81	22.97	3.21
18 February	9.60	29.68	22.89	3.08
26 March	9.10	29.24	22.64	3.09
21 April	9.20	29.52	22.84	2.73
17 May	9.26	29.56	22.85	2.32
17 June	9.34	29.76	22.99	1.69
9 July	9.44	29.49	22.77	1.27

Average rate of oxygen utilization from 26 March to 9 July = 0.018 ml/l/day

17 August	9.40	29.53	22.80	0.90
30 September	9.42	29.83	23.03	1.50
17 November	10.14	30.24	23.25	2.31

July 1954, reflecting the effect of accumulated runoff from melting snow. Rapid and apparently complete flushing of the water below sill depth occurred between October and November 1954, at which time the density of the water at the sill was greater than that of the water behind the sill.

That some vertical diffusion occurs at all times was indicated by the continuing change in temperature and salinity and by the decrease in density during those periods when the density below sill depth was greater than that in the overlying layers. The associated diffusion of oxygen was downward; however, the system never reached a steady-state condition of constant oxygen concentration in which the local consumption was balanced by downward diffusion. During the period July to September 1954 the concentration of dissolved oxygen decreased by 0.005 ml/l/day, the lowest rate observed. Thus there was a definite decrease in the apparent rate of oxygen utilization with time as the basin water aged and as the concentration of dissolved oxygen decreased. In general, the change in curvature of the oxygen concentration curves with depth ($\partial^2 [O_2]/\partial Z^2$) favored an accumulation of oxygen at the 180 m level; thus the actual utilization rates are probably somewhat greater than those shown by the rate of decrease of oxygen with time.

PORT SUSAN. A slightly different situation existed in Port Susan, which flushed out between August and September 1953 and which was then affected relatively little by diffusion and advection through January 1954; a second flushing started in February, with complete replacement in March. The local change in dissolved oxygen at a depth of 120 m in Port Susan averaged 0.017 ml/l/day for the period September 1953 to January 1954, or roughly 40 $^0/_0$ higher than the change below sill depth in the deeper Dabob Bay.

LYNCH COVE. In relatively shallow Lynch Cove, the circulation is restricted by the lateral configuration of the basin rather than by an entrance sill. At a depth of 30 m, two periods of decreasing oxygen concentration occurred, one in the spring of 1953 and another in the spring of 1954. The rates averaged 0.020 and 0.018 ml/l/day respectively, or about 70 $^0/_0$ higher than for Dabob Bay water entrapped during comparable periods.

GENERAL DISCUSSION

In all, some 150 separate determinations of changes in local oxygen concentration for Puget Sound waters gave an average decrease of 0.016 ml/l/day (5.8 ml/l/year), with the rates being somewhat higher in the shallow waters than in the deep basins. These rates in Puget Sound are high compared to consumption rates reported by others for the open sea: Redfield (see Rossby, 1936) estimated an oxygen consumption of 0.36 ml/l/year for a stagnant pool of water below sill depth in the Gulf of Maine; for the open Pacific off the California Coast at depths of 200, 400 and 700 m, Sverdrup and Fleming (1941) reported respective rates of 1.8, 0.6 and 0.05 ml/l/year; Riley (1951) estimated 0.21 ml/l/year for a depth of 200 m in the Atlantic Ocean, with rates decreasing at greater depths. The higher rate of oxygen utilization in the Puget Sound waters, as compared to offshore waters, may be due in part to the presence of a higher concentration of freshly-formed organic material in the water. It should be noted that water at a depth of 180 m in Puget Sound has not been away from the surface for more than a year or two at most, whereas water at 200 m and deeper off the California Coast may have been away from the surface for many years. Particulate matter, partly organic in nature, is subject to oxidation as it settles through the water mass. Presumably the relative concentration of the less-easily oxidized matter increases with depth below the surface although the total concentration decreases. Riley (1951) estimated that in the Atlantic only 10 % of the organic matter produced in the photic zone is oxidized below a depth of 200 m.

However, the depth of water behind sills, as in Puget Sound, is not a true measure of its isolation from the surface because the local water often circulates quite freely throughout the water column above sill depth, more or less continuously resupplying new-mixed water from near the surface to that depth. This would insure a rather rapid feed-rate of organic matter to depth, which is in agreement with the quite high rate of oxygen decrease below sill depth.

The higher rates of decrease in concentration with time in the shallow basins of Puget Sound as compared to those of deep waters probably represent a real difference in the rate of utilization, but the effects of diffusion and advection are especially difficult to estimate in shallow water. An example of the type of advection which can lead to high rates of change in local oxygen concentration, erroneously high if interpreted as oxygen utilization rates, is that which occurs at the heads of inlets. Water in the bottom of a basin, when displaced by new water of greater density during the flushing period, will rise to a level just below the halocline in the upper layers. This low oxygen water in turn displaces local water of high oxygen concentration from its previous position. The local change in oxygen concentration, which in such cases may amount to 0.27 ml/l/day, is due primarily to the effects of advection and not to the effect of local utilization. Associated with this vertical movement, which normally occurs in the fall, concentrations as low as 1.0 ml/l or 14 $^0/_0$ saturation have appeared within 5 m of the surface in Lynch Cove. Fish-kills have been reported in the fall in Holmes Harbor at about the time when low-oxygen water is normally displaced from the bottom and rises toward the surface, but an association of these events has not been documented.

The water entering the Puget Sound system near Port Townsend varies in dissolved oxygen concentration from 6 to 3 ml/l at the time of entrance. On the basis of an average oxygen utilization rate of 0.016 ml/l/day, and in the absence of downward diffusion, water remaining at basin depth in the system for about one year would be depleted of oxygen. The effect of locally introduced pollutants in reducing local oxygen concentrations cannot be evaluated correctly in the absence of suitable background knowledge of the natural oxygen regime and circulation patterns. Lack of this background information has confused industrial, plant, and sanitary engineers in assessing the effects of industrial waters in Puget Sound. It is of interest to note that at midchannel locations the rate of decrease in dissolved oxygen concentration with time was essentially the same in Dabob Bay and Lynch Cove, both of which border thinly populated nonindustrial areas, as it was in Port Susan near a heavily populated industrial area. In contrast to midchannel locations, however, waters near shore may be appreciably affected by local contamination.

The difference in concentration of dissolved oxygen from place to place along a given flow pattern, in conjunction with local utilization rates, can be used to obtain the difference in relative "age" of water between various places or to obtain a measure of the time it takes for water to move from one place to another. In this rough approximation it is assumed that the effect of diffusion on the oxygen concentration is negligible compared to the rate of chemica tilization. Using this approach, it has been computed on the basis a year's observation that bottom water at Point Jefferson averages out 10 days older than that at Point No Point, located 10 miles pstream toward the entrance sill. This is roughly the order of agnitude found from a consideration of the temperature of bot- m water following the onset of a period of unusually cold weather the Puget Sound area in mid-January 1954. Since the gradients oxygen concentration are at times much greater than those of conservative properties of temperature and salinity, the distrib- ion of oxygen and its changes with time should lead to a more alistic interpretation of circulation patterns below the photic ne than is possible from consideration of only the conservative operties.

SUMMARY

The changes of local oxygen concentration with time have been etermined for selected basin waters in the Puget Sound system. he average rate of oxygen utilization was 5.8 ml/l/year (0.016 l/l/day), which is high in comparison to offshore water. The xygen utilization rates in the best documented regions of Puget ound decrease somewhat with a decrease in the concentration of issolved oxygen, and individual localities show that there is a efinite decrease in the rate of utilization with an increase in the ime that the water had been standing in the basin. The next step this study should provide a picture of the changing oxygen re- ime in selected deep basins at close-spaced intervals of time and pace. For example, by monitoring discrete clouds of water in Dabob ay, where unique temperature and salinity characteristics are xhibited, it may be possible to evaluate oxygen changes in the bsence of the usual boundary effects and thus estimate more losely the rates of utilization as associated with individual parcels f water.

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EUROSECRETORY CELLS IN THE CIRRIPEDE, *POLLICIPES POLYMERUS* J. B. SOWERBY[1]

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ABSTRACT

A detailed morphological description of neurosecretory cells in the pedunculate rnacle *Pollicipes polymerus* J. B. Sowerby (Cirripedia) is given. The general anatomy its central nervous system conforms to that in other pedunculates. Some neurons the central nervous system are specialized for secretion and are uniformly stributed in all of the ventral ganglia and in the brain. The two types are: a large and irregularly pyriform cell-type with strongly chromophilic cyto- asm, nuclear acidophilia, Nissl substance in a perinuclear zone, peripheral aggre- tes of neurosecretory granules, and a vacuolate periphery; and (2) a smaller unded type having large vacuoles in a weakly staining cytoplasm and having the urosecretory granules close to the nucleus. Some observations on the secretory cle of the granules are given for the large cell-type. Axon transport of the granules as evident but no storage-release structure could be found. Neurosecretory activity this species is compared with that in other Crustacea, the possible mode of hormonal scharge is discussed, and direct discharge from the cell-body periphery is postulated. e possible functional aspects of neurosecretion in the cirripides are reviewed and eas where there is need for further search for endocrine mechanisms are indicated.

INTRODUCTION

The importance of neurosecretory activities in the physiology of any crustaceans is apparent from several recent reviews (Scharrer,

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1955; Welsh, 1955; Knowles and Carlisle, 1956[3]). It has also bee
stressed by Barnes (1959) and by Bookhout and Costlow (1959
that further advances in our understanding of the physiology an
ecology of the cirripedes will be delayed until something is know
about the control of many of their activities, particularly growth
moultings and reproduction. It is these activities that might be ex
pected to be under hormonal control and in which neurosecretio
could well be expected to play an important part.

Until recently the occurrence of typical neurosecretory cells i
the Cirripedia (Barnes and Gonor, 1958), or indeed in any othe
Entomostraca (Sterba, 1957), had not been reported. We have no
demonstrated their occurrence in a number of operculate barnacle
commonly found in the San Juan Archipelago, Washington; thes
include the intertidal species, *Balanus glandula* Darwin and *Chtha*
malus dalli Pilsbry, as well as the sublittoral species, *Balanus nubilu*
Darwin, *B. hesperius laevidomus* Pilsbry, and *B. rostratus* Hoek
However, in this account (unless otherwise stated) we confine our
selves to the pedunculate, *Pollicipes polymerus* J. B. Sowerby, be
cause at this time its neurosecretory cells are much more easil
demonstrated than those in the operculates examined.

P. polymerus is common in the middle and low tidal zones, espec
ially in exposed situations, along the Pacific Coast of North America
In the relatively quiet waters of the San Juan Archipelago it oc
cupies a rather specialized niche high up in the intertidal, wher
local shore topography in relation to waves and swell provide
conditions in which this animal can feed.

MATERIAL AND METHODS

Fresh newly collected animals were used. Either the nerve cor
was dissected out under sea water as quickly as possible, or th
whole body was rapidly removed from the mantle cavity. Th
material was then transferred to one of the following fixatives
formalin, Bouin's, or Zenker's with acetic acid. The formalin-fixe
material was for the most part postchromed with 2.5 $^0/_0$ potassiu
dichromate to improve fixation. After dehydration in alcohol an
clearing in toluene or after dehydration and clearing in tertiar
butyl alcohol, the material was embedded in paraffin ('Tissuemat')
Most of the sections were cut at 8–10 μ, but some were cut at 5 μ

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[3] See also Carlisle and Knowles, 1959.

he following staining techniques (some particularly for examination the neurosecretory material, others for a general histological cture of the nervous tissue) were employed:

(a) Paraldehyde-fuchsin, Gabe's (1953) modification of Gomori's technique (PF);
(b) Gomori's chrome-haematoxylin (CH) and chrome-haematoxylin with philoxine (CHP);
(c) Paraldehyde-fuchsin with either toluidine blue or chrome-haematoxylin;
(d) Ehrlich's haematoxylin and eosin (HE);
(e) Periodic acid-Schiff routine, with the addition of an acid sulphite rinse after the Schiff reagent (PAS);
(f) Sudan Black B, mounted in an aqueous medium;
(g) Toluidine blue in an aqueous medium;
(h) Masson trichrome technique.

NERVOUS SYSTEM AND CELL-TYPES

General Description of the Nervous System. The general anatomy f the nervous system of the genus *Pollicipes* has been studied y Darwin (1851) using *P. mitella*, by Nussbaum (1890) using *. polymerus*, and by Batham (1945) using *P. spinosus*. The central ervous system of *P. polymerus*, which conforms to that of other edunculate cirripedes, has a supraoesophageal ganglion (brain) onnected by oesophageal commissures to the large suboesophageal anglion of the ventral nerve cord, which has only four thoracic anglia, of which the suboesophageal is the largest, as Batham 1945) found for *P. spinosus*. The ventral ganglia of *P. polymerus* re laterally bilobed and are rather less crowded together than hose figured for *P. spinosus* by Batham (1945: plate 50, fig. 9); lso, the double ventral connectives are clearly visible. In cross-ections of the whole animal, perineural blood spaces similar to hose described by Cannon (1947) for *Lithothyra* surround the ganglia.

The freshly dissected nervous system did not show any localized lue-white refractile appearance which is characteristic of fresh ecapod neurosecretory tissue. However, the surface of the main anglia, and particularly that of the suboesophageal ganglion, of reshly dissected material is often white and opaque in contrast to he more transparent appearance of the rest of the nervous system.

Both the nerve cord and the peripheral nerves are surrounded by a thick compact sheath, 10–15 μ thick (see margin of Plate 1, Fig. 1), which is made up of two layers of connective tissue fibres—a thin outer and a thick inner layer.

In PF preparations, fibres of the outer layer stain an intense purple, indicating that they are elastic fibres (Gomori, 1950); in HE preparations the outer layer is less eosinophilic than the inner. The elastic fibres, which are ovoid in cross-section and range from 1.0–1.5 μ in diameter, can be individually resolved; they run lengthwise along the nerve cord and often overlap each other to give the appearance of a loosely interlaced meshwork.

The inner layer stains pale red with the PF technique and is strongly eosinophilic. The individual fibres are not easily distinguished; small elongated nuclei, such as those commonly found in connective tissue, may be seen in sections stained with HE. This layer is metachromatic with toluidine blue, PAS-positive, and stains like collagen with Masson's trichrome technique.

The large suboesophageal ganglion of all of the species of barnacles examined has one distinctive character; each of the two lobes contains a centrally located, sharply defined area within the neuropile. These areas are shown only by the PF technique which stains them deeply. In *P. polymerus* such areas are separated by a region of large axons which occasionally contain neurosecretory granules. Similar large axons, passing for the most part dorsoventrally, are also present lateral to these areas. At first the densely staining areas were considered areas of granule accumulation, but more detailed examination has shown that they are composed of small axons and that the densely stained material is not in the form of granules. These areas apparently do not then represent 'storage areas' and their relation if any to neurosecretory activities is unknown, since it was not possible to determine the origin of the small nerve fibres. Nevertheless, the presence of neurosecretory granules in the large axons here and elsewhere indicates that axon transport occurs in this species although it was impossible to trace its course.

Scattered throughout the neuropile area of all ganglia, in the commissures and in the bases of the larger nerves, are small nuclei, 4–5 μ in diameter, which are presumed to be the nuclei of neuroglial cells. These basophilic nuclei, with their small basophilic nucleoli, are irregularly spherical. Only in a few cases can a small cell-body be distinguished around the larger of these nuclei. Because the cytoasm of these cells is not basophilic, it is difficult to differentiate em from the surrounding neuropile. They are occasionally found sociated with the small neurons, but they were not found close the large cell-type (see below for cell-types).

A striking feature of the histology of the nervous system of *polymerus* is the apparent absence of 'ordinary neurons'. Usually 'brain' and other ganglia of arthropods have central or peripheral eas, *e. g.*, the corpora pedunculata of insects, where small neurons, h small round nuclei and a restricted amount of cytoplasm, are owded together. These are sometimes termed 'association neurons'. atsumoto (1954b: fig. 11) has illustrated such a group of small, nsecretory neurons from the thoracic ganglion of the crab, *Eiro-eir.* In contrast, all identifiable neurons in the central nervous stem of *Pollicipes polymerus* show some cytological specialization.

Two types of neurons, both of which contain neurosecretory ranules, were found in the central nervous system of *P. polymerus.* he cell-bodies surround the central neuropile of the ganglion. The ost conspicuous cell-bodies in sections of the ganglia are large and regularly pyriform with abundant, strongly chromophilic cyto-lasm and with their Nissl substance concentrated in a zone around he nucleus; small vacuoles, described below in detail, are found round the periphery of these cells. Another type, smaller than this, rounded and contains cytoplasm which is extremely vacuolated nd which does not stain strongly.

Observations on the Large Neurosecretory Cell-type. These neurons re about 30–45 μ in diameter with an oval nucleus 12–15 μ in iameter (in fixed sections). The cytoplasm is basophilic, with the issl substance in a zone around the nucleus. The nucleus has a ensely staining basophilic membrane and a markedly acidophilic ucleoplasm which characteristically was pulled away from the embrane regardless of the fixative used. The single nucleolus is arge, basophilic and invariably found against the nuclear mem-rane. These cells are found in all ganglia, including the supra-esophageal, which shows no specialization that distinguishes it rom ganglia in the ventral nerve chain.

The PF technique shows the presence of granules that stain deep urple in both cell-types. The only other technique that demonstrated hese granules was the PAS procedure. In the large cell-type the ranules usually occur in aggregates just outside the Nissl zone, in an area where the cytoplasm is less basophilic. In addition, aggregates are often present at the extreme periphery of the cell both at the axon hillock and in the large axon itself as it leaves th cell. These large axons (diameter c. 10 μ) have neurofibrils and thin but distinct membrane which does not stain with Sudan Black Random sections of such large tubular axons often show granule located within them and against the axon membrane.

Observations on the Small Neurosecretory Cell-type. These cells about 20 μ in diameter, are characterized by their extensive vacuolation, each cell containing a few large vacuoles that almos completely fill the cytoplasm. The contents of these vacuoles ar not PAS-positive nor do they stain with any other method used The spherical nucleus, 6–8 μ in diameter, contains acidophilic nucleoplasm. Neurosecretory granules similar to those in the larg cells are present in the cytoplasm and are particularly concentrate around the nucleus. At present, no stages in the secretory activit of this small cell-type have been distinguished. Their appearance i the same with all fixatives used, apart from some variation in th apparent extent of vacuolation. These cells appear to be mor numerous in the anterior and posterior peripheral parts of the ventral ganglia where the ventral connectives arise and less numerou than the large cells in the lateral, dorsal, and ventral periphera regions of the ganglia. They are also scattered among the larg cells in the supraoesophageal ganglion.

Observations on the Production of Granules in the Large Neurosecretory Cell-type. Although the entire cycle of formation an release of neurosecretory granules has by no means been completel determined, a number of pertinent observations have been made Those large cells which appear to be at the beginning of granul production are characterized by intense reddish staining of th cytoplasm with PF and by strong basophilia with haematoxyli and toluidine blue (Plate 1, Figs. 1, 2). Usually the cytoplasm i dense and finely granular. The Nissl zone stains more strongl than the periphery (Plate 2, Fig. 5). Fully-formed granules, abou 1 μ in diameter and staining a deep purple (PF), are peripheral t the Nissl zone. In the Nissl area, close to the nucleus, a few smal purple-staining (PF) granules may occur; these are probably th precursors or an incomplete form of the neurosecretory granules Between the peripheral aggregates of fully developed granules an

e most densely staining region of the Nissl area, a few purple-
aining granules of intermediate size are occasionally found
late 1, Fig. 2). It is suggested, therefore, that the granules move
ripherally from a point of origin in the Nissl zone.

The Nissl substance itself is in the form of fine basophilic gran-
ations in an area of basophilic cytoplasm. By combining the PF
hnique with toluidine blue or Gomori's chrome-haematoxylin,
issl basophilia and neurosecretory granules may be demonstrated
the same preparation (Plate 2, Fig. 7). The granules are purple
contrast to the blue Nissl area; in addition, a few purple-staining
anules of small size can be distinguished among the basophilic
issl granulation.

Cells that appear to be further advanced in the secretory cycle
e characterized by reduction in intensity of paraldehyde-fuchsin
aining of both the general cytoplasm and the Nissl zone. At this
age the cytoplasm is less dense and more coarsely granular than it
earlier. The granules are present at the periphery of the cells
here the cytoplasm stains lightly (Plate 2, Fig. 5), and immediately
eripheral to the granules is a zone of fine vacuolation. In later
ages, this zone becomes wider and is accompanied by a decrease
the staining intensity of the Nissl zone itself. The granules are
ow closely applied to the inner edge of the vacuoles which they
artially surround (Plate 2, Fig. 7; Plate 4, Fig. 15); a few granules
f intermediate size can still be recognised between the nucleus
nd the peripheral concentrations of granules. In cells at this and
t the somewhat earlier stage, some sections show granules in the
xon as it leaves the cell (Plate 3, Fig. 10).

There are occasional scattered cells which also appear to be in an
ntermediate stage of the cycle of granule production and discharge.
hey are of the same size range and same general appearance as
hose already described. However, the cytoplasm is packed with
ranules in contrast to all other stages where the granules are
eripheral. In these cells the cytoplasm between the granules stains
nly lightly; in some cells the granules themselves, instead of being
omogeneous discrete particles, appear to show signs of disintegration.

The next stage observed seems to be one of depletion and degen-
ration (Plate 2, Fig. 8). The absence of cells showing a gradual
ransition between this and the intermediate stages described sug-
ests that this final stage may be reached rapidly. It would appear
hat, as these degenerative processes take place, the cytoplasm,

finely vacuolar rather than dense, stains less strongly and that the Nissl zone becomes narrow and stains weakly. The only granule present are closely applied around peripherally located large vacuoles. In some cases there may even be PF-positive amorphou substance around the vacuoles, suggesting disintegrating neurosecretory granules.

Some Reactions of the Granules and Vacuole Contents. Section stained by the PAS technique give some information on the natur of the granules and their movement. The large neurons are characterized by an extensively developed peripheral zone of vacuoles These vacuoles do not take ordinary stains but give a strong positive reaction to PAS, so that the large cells are sharply delimited by the red coloured zone of the densely staining vacuole (Plate 3, Figs. 9, 10, 11). While these vacuoles stain deep red, th neurosecretory granules themselves stain less strongly – varying from pink to red. The PAS-positive reaction indicates the presence o carbohydrate in these structures, since periodic acid oxidation i necessary to produce the PAS staining; the Schiff reagent withou prior oxidation does not give a positive reaction. Furthermore sections from the same series as those used for PAS staining showed no indication of lipid material in the vacuoles or granule (demonstrable by the Sudan Black technique), nor is the materia metachromatic with toluidine blue in aqueous mounts. Both buffered and unbuffered malt diastase as well as saliva remove th PAS-positive material from the vacuoles in about 15 minutes a room temperature with 10 μ sections (Plate 3, Fig. 12; Plate 4 Figs. 13–15).

The neurosecretory granules vary in their reaction to the PAS procedure, staining from pink to red. Those in the cell-body are usually less intensely stained than the vacuoles, but on occasion granules in the periphery of the cell-body and in the axon stain deep red. It has been noted that in certain preparations the granule in some cells may be distinctly positive, in others faintly positive The PAS staining property of the granules is unaffected by enzymatic digestion in the time required for complete removal of thi property from the vacuoles (Plate 3, Fig. 12; Plate 4, Figs. 13–15) The cytoplasm, particularly that of the Nissl zone, sometime stains moderately PAS-positive, the degree varying from cell t cell; enzymatic digestion does not remove the staining property.

Note that in sections of both the whole animal and of the dis-cted nervous system, with all fixatives used, the strongly PAS-sitive material in the vacuoles was present, distributed all around e cells. There was no evidence of fixation drift.

Tests show the presence of carbohydrate in the vacuoles; its AS-positive character together with its removal by amylase gestion suggests that it is glycogen, but this interpretation is open question in view of the ease with which it is preserved in the atives employed. Certainly, the material is not lipid (negative dan Black, positive amylase digestion).

Neurons in Sexually Immature Animals. Some preliminary work as done on sexually immature individuals; serial sections were epared from formalin-fixed, postchromed, whole bodies of small *polymerus* that were attached to adults. Although these adults owed the typical neurosecretory granules, none was found in e juveniles with either the PF technique or with CHP. However, wo types of neurons were present–a large type with nuclear acid-ophilia, strongly basophilic cytoplasm and a wide, densely baso-hilic Nissl zone as well as a small type with vacuoles. The large ells showed little peripheral vacuolation, and neither type had any ffinity for the paraldehyde-fuchsin stain. Since the adults to which e small animals were attached were treated in the same manner nd showed neurosecretory granules, it is unlikely that the absence f the latter in the juveniles was due to technique.

DISCUSSION

Comparison with Neurosecretory Activity in Other Animals. Apart rom a preliminary note (Barnes and Gonor, 1958), it is believed hat this is the first account of neurosecretory cells in the Cirri-edia and only the second time that these cells have been recorded the Entomostraca (see Sterba, 1957). In general, the appearance f the large neurosecretory cells in *P. polymerus* resembles closely hat of cells described in the thoracic ganglia of some other Cru-tacea. Miyawaki (1956a, b), in his work on *Telmessus cheira-onus*, observed the aggregation of Nissl substance around the ucleus, the presence of peripheral vacuolations containing PAS-ositive carbohydrate material, and the occurrence of uniformly ense, finely granular cytoplasm (1956b: plate 26). The similarity also extends to the pronounced variability of different cells with regard to their moderately positive cytoplasmic PAS reaction. It is also of interest to observe that, although Miyawaki (1955) first doubted whether the extensive vacuolation seen in sections o fixed material corresponded to that area of watery periphera cytoplasm observed in living cells under phase-contrast, he was later (1956b) able to demonstrate vacuolations in living cells. Smal types of neurosecretory cells have been repeatedly described in other Crustacea. In view of the great diversity of neurosecretory cell-types, a detailed comparison is not warranted, but attention may be drawn to the resemblance of the small cells described by Miyawaki (1956a, b) in *Telmessus* and by Matsumoto (1954b) in *Eriocheir* to those described here.

The distinctive features of the nuclei in the large neurosecretory cells of *P. polymerus*, namely their large size and the marked acidophilia of their contents, recall similar features in the large neurosecretory cells described by Matsumoto (1954b). These findings support the suggestion that the nucleus in such cells may be involved in the secretory process (Scharrer and Scharrer, 1945). From our evidence, it seems that recognizable neurosecretory granules arise in the zone of Nissl bodies and basophilic cytoplasm around the nucleus and that, from this region, they move peripherally; as more granules are produced, the width and intensity o staining of this zone decreases—a correlation that has frequently been observed in other neurosecretory cells (Scharrer, *et al.*, 1945 Scharrer and Scharrer, 1945). These observations suggest that the RNA-rich Nissl substance is playing an active part during the formation of the secretory product.

We have been largely concerned with the central nervous system However, sections of whole bodies showed no evidence of storage organs either in *P. polymerus* or in any of the operculate species examined. No obvious tracts containing neurosecretory materia could be found leaving any portion of the ganglion chain. However the possibility remains that there is in barnacles a storage release center quite distinct from the central nervous system. Matsumoto (1956) has demonstrated that in *Chionoecetes* the staining properties of the neurosecretory granules are radically changed as soon as they enter the axon; thereafter their form is also rapidly changed with loss of individuality and eventual disappearance as discrete particles. If this type of change occurs in *P. polymerus*, then it has ot been shown by the technique used thus far; the fate of gran- les in the axon remains unknown.

In view of the apparent absence of a storage-release organ, the ossibility that discharge may take place directly from the cells emselves assumes even greater importance than otherwise. That scharge may take place, at least in part, at the periphery of the ll-body and that the vacuolar contents are involved is indicated y the close association of the neurosecretory granules with the eripheral vacuolation. Vacuolations in neurosecretory cells have ot only been described repeatedly but have often been correlated ith the production and discharge of secretory material. Direct scharge from neurosecretory cell-bodies may indeed be more ommon and more important than is usually envisaged even in ose animals with axonal transport and storage-release organs. rogressive vacuolation and in some cases strong peripheral vacuo- tions have been found by Scharrer (1941) in cockroaches; by charrer *et al.* (1945) in several lower vertebrates; by Matsumoto 954a, b), Parameswaran (1955, 1956), and Miyawaki (1956a, b) n several genera of crabs; by Durand (1956) in crayfish; and by abe (1954) in heteropod gastropods. Perhaps these findings indi- ate some direct discharge.

Furthermore, Matsumoto (1954a, b, 1956) concluded from his bservations that in the thoracic ganglion of *Chionoecetes* peripheral ischarge is accompanied by axon transport whereas only peripheral ischarge from the cell-bodies occurs in this ganglion of *Eriocheir.* He cites several other examples of this double mode of discharge. That both types of discharge may take place in *Pollicipes polymerus* s indicated by the fact that the same cell may show granules closely ssociated with peripheral vacuoles and in the base of the axon s well. Note also that Matsumoto (1954a, b) has described 'capil- aries' surrounding the large neurosecretory cells of a crab thoracic anglion and that Parameswaran (1956) found 'blood vessels' imilarly situated. In this way any material discharged at the periph- ry of these cells may be taken into the haemolymph. There is o such system in *P. polymerus.* Nevertheless, in barnacles the mass f nervous tissue in the ventral ganglion is much less than that in crab; furthermore, all cell-bodies are very close to the margins f the ganglia. In addition, the whole ganglionic chain is immersed n a blood space–the perineural blood sinus. Thus the cell-bodies ie in close proximity to the body fluid, and diffusion into it may be the mechanism by which active material reaches the body fluid In any scheme such as that proposed by Welsh (1955), the lack o any storage organ or any specialized 'glandular areas' for neurosecretory products puts the Cirripedia in a more 'primitive' stag in relation to other Crustacea and to Insecta.

The only other entomostracans in which neurosecretory cells ar known are *Daphnia* and *Simocephalus*, as recently described b Sterba (1957). In *Daphnia* these cells are small (10 μ in diameter) few in number, and localized in five groups in the brain and suboesophageal ganglia. It has been shown that they form granule that are carried into the axons. Sterba could not find neurosecretor cells in the optic ganglion, nor were there any such cells or store neurosecretory material associated with the naupliar eye, the compound eye, or the frontal organ.

P. polymerus resembles *Daphnia* in the absence of a storage release organ and in the fact that neurosecretory cells are not associated with the optic ganglion or with the naupliar eye.

Functional Aspects of Neurosecretion in the Cirripedia. In th Malacostraca, structures associated with the eye and eye stal (sinus gland, X-organ) are particularly involved with various form of neurosecretory activity. These endocrine structures vary greatl in organization and complexity (Hanström, 1939), yet in n form do they appear to have any counterpart in the Cirripedia It must be stressed, however, that the cirripedian adult eye i extremely different from, and indeed not homologous with, th compound crustacean eye. In the Cirripedia, free-living nauplia Stages I–V have a single median eye which does not, according t Fales (1928), have a double origin; it has a central, heavily pigmente area and a nonpigmented area with two visual cells. Paired eyes found in the Stage VI nauplius, become fully developed in th cyprid and resemble the compound crustacean eye (Darwin, 1851 Hesse, 1874; von Willemöes-Suhm, 1876; Fales, 1928). During th change to adult, however, these compound eyes, after some migration and absorption, are cast off at ecdysis with the carapac of the cypris (Doochin, 1951). The naupliar eye remains; and eventually, after dividing into two parts, it gives rise to the paired eye (often fused) of the adult; subsequently these come to lie dee within the body and are attached by fibrous tissue to the radiatin muscles of the lower part of the oesophagus. It is necessary fo

ht reaching the eye to pass through the exterior membrane and
derlying corium connecting the two scuta so that it can pene-
te deeply into the body. In view of these facts, it is not sur-
sing that we have been unable to find a structure associated with
eye in either *P. polymerus* or in balanids that may be interpreted
being involved in neurosecretory activity.

n the structure of the eye and in the absence of any chromato-
ore system, the Cirripedia stand in marked contrast to many
er crustaceans. Cirripedes are sensitive to light, however, as
denced by the so-called ‘shading reflex’; during cirral beat, the
rcular valves close when the animal is subjected to a sudden
nge in light intensity from above. The sensitivity varies ac-
ding to the species, but in those cases examined, the eye is the
ective receptor (Fales, 1928). The reaction is presumably a de-
nce mechanism against those predators which, approaching from
ove, cast a shadow; this is the case with inshore fishes, which are
rticularly active in this respect and which often bite off the cirri
d sometimes take the body. However, there is evidence that in
any cases neurosecretory processes are in some way (as yet little
derstood) under the influence of light, and it is suggested there-
re that the cirripede eye, divorced from many of its usual functions
d indeed not homologous with the compound crustacean eye, may
ill serve as a receptor to mediate between light changes and neuro-
cretory activity; indeed this may be its most important function.
this were the case, then it would be easy to explain some of the
asonal changes in activity that take place under conditions where
ght intensity appears to be the only major variable of the envi-
nment.

In their discussion of crustacean hormones, Knowles and Carlisle
956) have distinguished between those endocrine mechanisms
hich are immediately adaptive (energetic hormones) and those
ncerned with the more gradual processes of growth, development,
d maturation (metabolic hormones). In view of the foregoing it
ight be anticipated that the energetic hormones would be absent
the cirripedes; the absence of a normal compound eye, of chro-
atophores, and of retinal pigment systems, all lend support to
is view.

We may now consider the metabolic hormones. Here again it
ay be anticipated that in the cirripedes there will be considerable
riation from the pattern in other crustaceans – possibly with some

'simplification'. Some of the most fundamental processes know to be associated with metabolic activity in the Crustacea are thos relating to the moulting cycle, and in these the eye-stalk comple appears to play a part by producing a moult-inhibiting hormone However, Carlisle (1953a, b) has suggested that the neurosecretor cells in the thoracic ganglion of shrimps may also play a part i moulting. By far the greater part of this work on the relation between moulting and hormonal activity has been done on Brachyur and Astacura, in which the moulting cycle is complex and intimatel bound with calcium metabolism; in cirripedes moulting appears t stand in some contrast to that in these groups of higher Crustacea Barnacles often moult rapidly and continuously and, under favourable conditions, they may moult every few days. Costlow and Bookhout (1953) have shown that *Balanus improvisus*, maintained i laboratory culture, moults every 2–3 days and that the moultin regularity is in part dependent on the type of food. Further, the found no indication of a correlation between shell growth (*i. e.* calcium carbonate deposition) and moulting. Recent work o *B. amphitrite* var. *niveus* by Costlow and Bookhout (1956, 1957 Costlow, 1956) gave a similar high rate of moulting which wa independent of various changes in conditions of illumination; again no association between the moulting cycle and shell growth coul be demonstrated. In contrast to the condition in decapods, therefore, there is some evidence that certain phases of the calcium metabolism in cirripedes have been divorced to a large extent from the moulting process. (There are, of course, stalk-eyed Crustace which have sinus glands but which do not lay down a calcareou skeleton.) The continuous and rapid moulting of cirripedes suggest a situation similar to that found in *Lysmata* (Carlisle and Dohrn 1952, 1953; Carlisle, 1953b), where the moult inhibitor is absent a moult-accelerating hormone is present in the eye-stalk and in th thoracic ganglion and brain.

In their reproductive activities, cirripedes are again atypical o the Crustacea. Although there are females and dwarf parasitic male as well as hemaphroditic individuals in a few pedunculates, *e. g.* in *Ibla* and *Scalpellum*, most cirripedes are hemaphroditic, an obligate cross-fertilization is general yet not essential (see Barne and Crisp, 1956; Barnes and Barnes, 1958). It seems probable therefore, that the hormonal organization in cirripedes will diffe considerably from that found in other crustaceans where the sexe e usually separate and where distinctive secondary sexual charters are known to be directly under hormonal control.

Some cirripedes breed only annually (*e. g.*, *Balanus balanoides* and *balanus*), and these are Boreo-Artic forms. Others, typically warmter species, may breed all year round with variable intensity, t only during summer months in the northern parts of their ge. However, certain species which in many respects are typically eo-Arctic or Temperate in behaviour (*B. crenatus* and *B. glanla*) do not entirely retain the single annual brood at their south limits (Barnes and Barnes, 1956). These species would repay ther investigation. Furthermore, it has been shown that release nauplii by some Boreo-Arctic species (*e. g.*, *B. balanoides*) is nchronized with the spring diatom increase over the whole range distribution (Barnes, 1957). In other species, *e. g.*, *Verruca stroemia*, e naupliar release tends to take place a short time before the ring diatom increase; the latter cannot, therefore, initiate the lease. It is possible that light, acting through the adult eye and itiating hormonal activity, may be involved; such action could cur either at the time of the release or at some time before it. the latter case, light might stimulate hormonal activity and us initiate processes that are not necessarily under direct hormonal control so that the naupliar release will occur at the time the spring diatom increase. It should be pointed out, however, at any such hormonal activity need not be only of a neusecretory kind.

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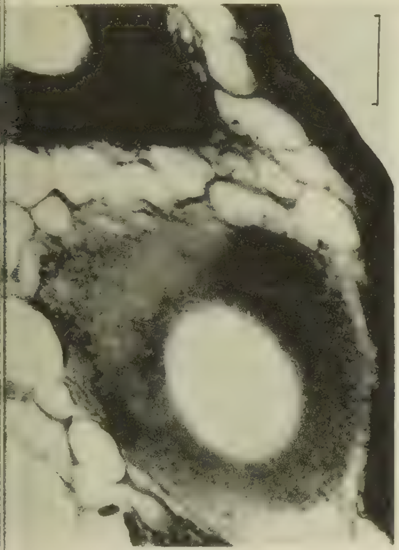


. 1. Bouin, PF, Hematoxylin. Early stage in retory cycle with few granules. Scale 10μ for figures.

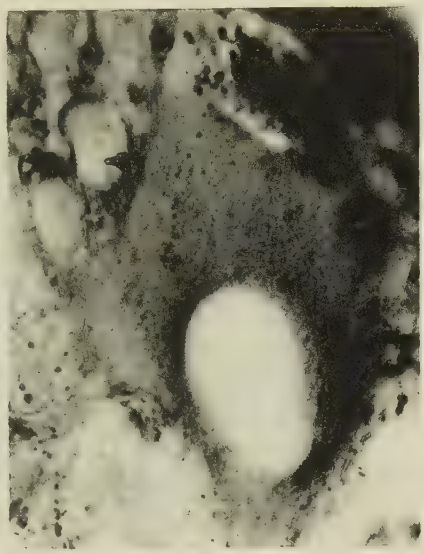
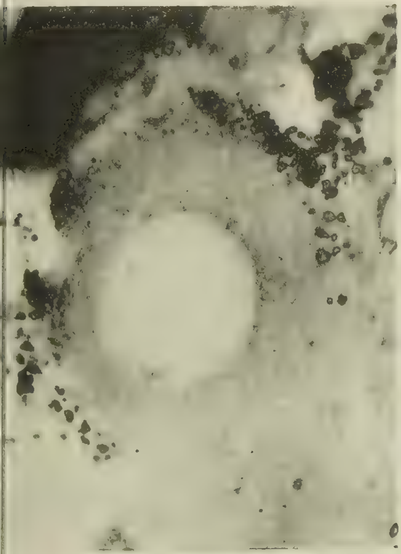


Fig. 2. Bouin, PF. Beginning of cycle; small granules near nucleus, large at periphery.



. 3. Bouin, PF. Granules now accumulated at rgin; some vacuoles present.

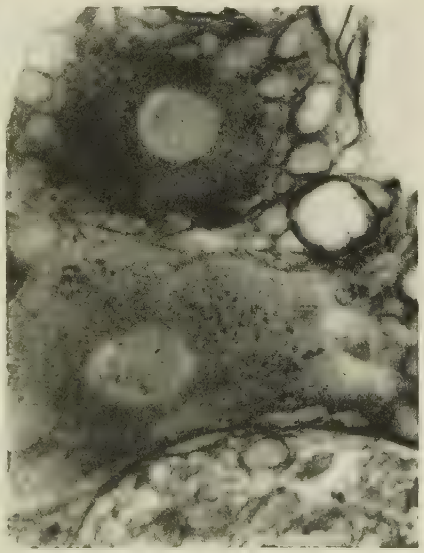


Fig. 4. Bouin, PF. Two cells of early stage. Note surrounding axons.

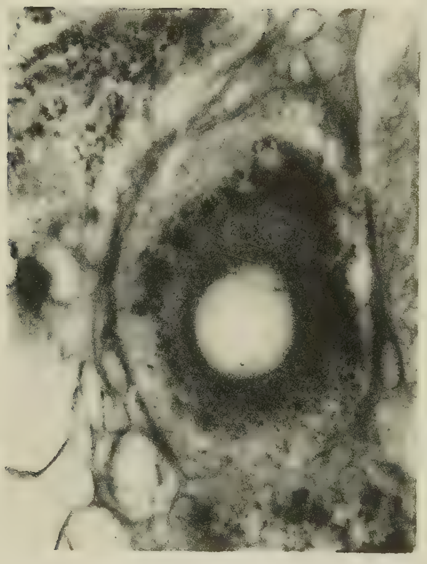


Fig. 5. Zenker, PF. Note peripheral vacuoles around margin, zone of granules just inside vacuoles.

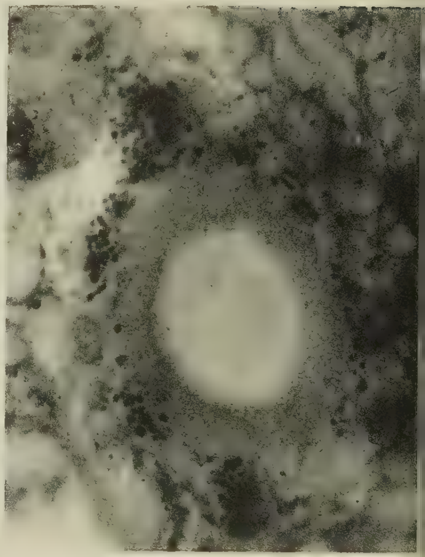


Fig. 6. Bouin, PF. Discharge phase. Peripher ally massed granules closely associated wit extensive vacuoles.

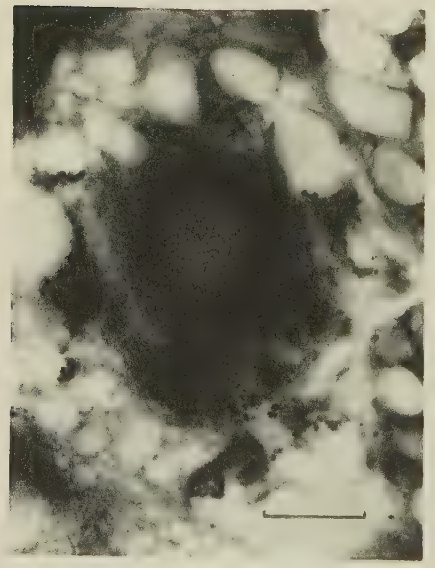


Fig. 7. Zenker, PF, Toluidine Blue. Discharge phase with narrow Nissl zone; extensive vacuoles with granules at their inner periphery.

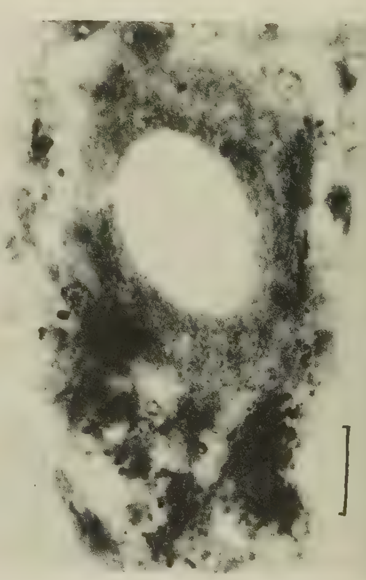
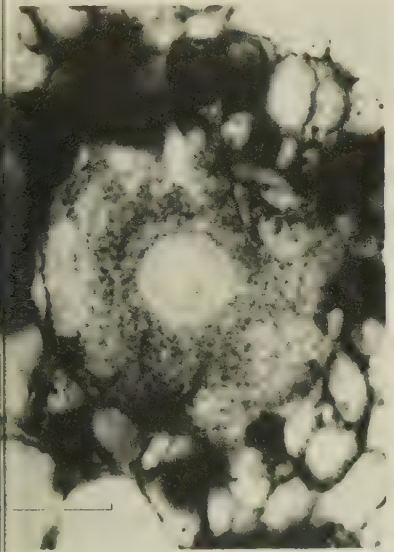


Fig. 8. Bouin, PF. Cell at cycle end. Cytoplasm vesicular, weakly chromophilic.



9. Zenker, PAS. Extensive peripheral uoles strongly PAS positive.

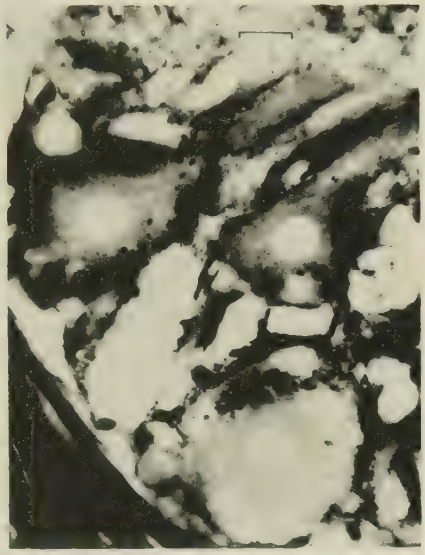
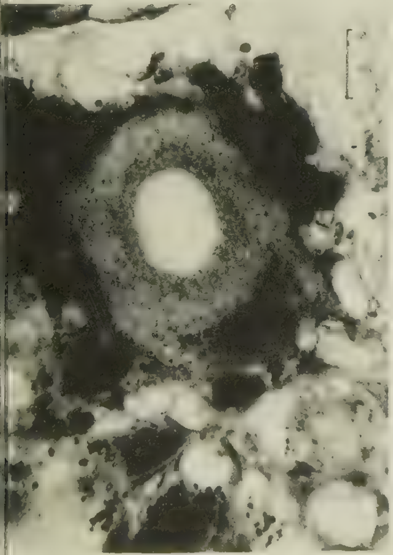


Fig. 10. Formalin, Post-chromed, PAS. Vacuoles and granules positive. Control for Figs. 12-15.



. 11. Formalin, Post-chromed, PAS. As Fig. but Nissl area moderately positive. Serial trol for Figs. 12-15.

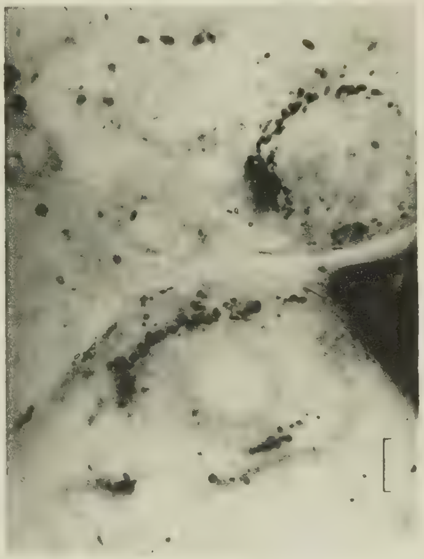


Fig. 12. Formalin, Post-chromed, Amylase, PAS. Negative vacuoles, Nissl area. Positive granules.

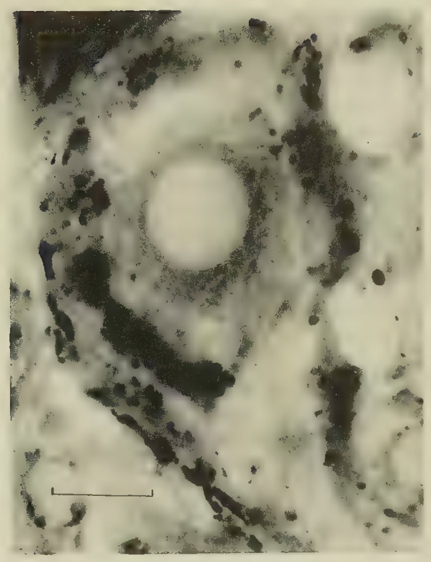


Fig. 13. Formalin, Post-chromed, Amylase, PAS. Negative vacuoles. Positive peripheral granules, Nissl area.

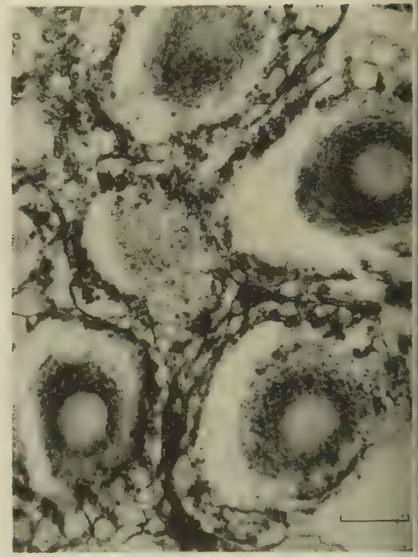


Fig. 14. Formalin, Post-chromed, Amylase, PA Vacuoles negative. Cytoplasm positive.

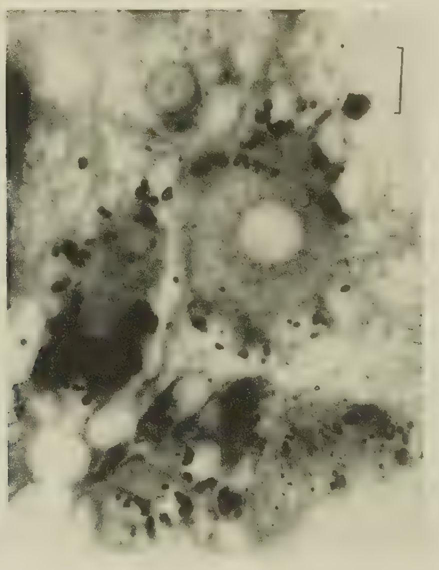


Fig. 15. Formalin, Post-chromed, Amylase, PAS. Positive granules closely applied to vacuolations.

ON THE RESTRICTED DISTRIBUTION OF TWO DEEP-SEA FISHES, *BOROPHRYNE APOGON* AND *STOMIAS COLUBRINUS*

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ABSTRACT

he restricted distribution of *Borophryne apogon* and *Stomias colubrinus*, both hypelagic fishes, is notable. Although relatively few specimens have been caught date, there is good evidence to indicate that their geographical distribution is ited. Knowledge about the epipelagic life of the early stages and about the hypelagic life of the adolescents and adults of these species has been combined h our recent knowledge of ocean currents in the Pacific (including the Cromwell rrent) to provide an explanation of their peculiar distribution.

INTRODUCTION

One may postulate that no animal species in the sea is rare. At ast it is not easy to conceive of breeding populations of marine ecies totalling only a small number of specimens, as is the case ith several terrestrial species, *e. g.*, some mammals and birds. Still any marine species are called *rare*, which in most instances prob- ly means only that they have been *caught rarely.* Be that as it ay, unlike the commercial fisherman or fisheries biologist, who n usually obtain specimens of a given species in as large quantities is desirable for study, the biologist of the oceans must be satisfied ith relatively few specimens. But, like the fisheries biologist, the eanic biologist would like to know how the distributional pattern a species is maintained, why it is rarely caught, etc. In short, too would like to obtain knowledge of a species' life pattern and stribution by employing, when possible, chemical and physical servations of a species' environment.

On the following pages, two deep-water species (*B. apogon* and *colubrinus*) are discussed, largely from a viewpoint of distribution. he 50 specimens of *B. apogon* used in this study may seem a ridi- lously small number compared with the thousands of specimens ndled by fisheries biologists, but the correlations and conclusions have been drawn along lines similar to those used for well know species. *S. colubrinus*, a more commonly caught fish than *B. apogon* provides a more or less parallel case to that of *B. apogon*.

Borophryne apogon Regan 1925

Early Collections. In 1922 the Dana Expedition caught four females of a deep-sea angler fish in the Gulf of Panama in open ring nets with 3500 m of wire out. They were described as a new genu and species, *Borophryne apogon*, by Regan (1925:564). The generi characters are so distinct that no other species has as yet bee described for this genus.

When the Dana again visited the Gulf of Panama in 1928, fou more specimens were caught: two females, each with a parasiti male attached to the abdomen. Thus far interest in the catch wa mainly a zoological one (Regan and Trewavas, 1932:106). I stil remember what a rare sight these specimens were when we got the from the deep. This later voyage of the Dana was under the leadership of Johannes Schmidt, and on her trip around the world th same methods of fishing were employed at all times. In the 801 ope ring-net hauls with 600 m wire or more, several bathypelagic specie showed a more or less cosmopolitan distribution, but *Borophryn* was taken only in the Gulf of Panama, in six hauls. Furthermor in some 2380 hauls with less than 600 m wire and open ring-net no *Borophryne* were taken anywhere.

Beebe and Crane (1947:171), who visited the Central America Pacific also, in 1925 and 1938, caught three females, two of the with parasitic males, all from the vicinity of the Cocos Island an the Gulf of Panama. They were taken with open nets presumabl from depths of 500 to 700 fathoms.

In 1951 Bertelsen revised all of the ceratioid fishes treated formerl by Regan (1926) and by Regan and Trewavas (1932), including th larval stages not studied by these authors. Bertelsen also identifie the free living males of *B. apogon*, four of which were larvae onl 7–16 mm long. Thus the number of *B. apogon* caught by the tw Dana Expeditions totals seven females and 28 males; in additio Beebe and Crane had taken their three females and two males. Al of these were taken in the Panamanian region.

Recent Collections. The Galathea Expedition 1950–1952, th Danish Deep Sea Expedition around the world, pursued an east

TABLE I. Borophryne apogon Regan collected by the Galathea in 1952

Sta.	*Date*	*Locality*	*Depth to Bottom* (*m*)	*Gear*	*Range of Catch* (*m*)	♀	♂	*Length* (*mm*) *Total*	*Length* (*mm*) *Stand.*
726	13 May	5°49′ N, 78°52′ W	3270–3670	Open otter-trawl	3670–0	1	..	*c.* 65	..
—	—	—	—	—	—	1	..	69	54
—	—	—	—	—	—	..	1	17	12
727	13 May	6°26′ N, 78°43′ W	3570	Pelagic otter-trawl	1150–0	1	..	52	40
—	—	—	—	—	—	1	..	60	44
—	—	—	—	—	—	1	..	83	63
—	—	—	—	—	—	..	1	19	13
—	—	—	—	—	—	..	1	*c.* 20	..
739	15 May	7°22′ N, 79°32′ W	915–975	Open triangular otter-trawl	975–0	1	..	74	57
—	—	—	—	—	—	1	..	79	58

ward course, in the opposite direction of the westward-bound Dan in 1928–1930. There was little pelagic fishing, but quite large bottom trawls (foot-rope 32 m) were used. These open nets brough up a considerable number of pelagic organisms caught between th bottom and the surface, among them a number of ceratioid fishes

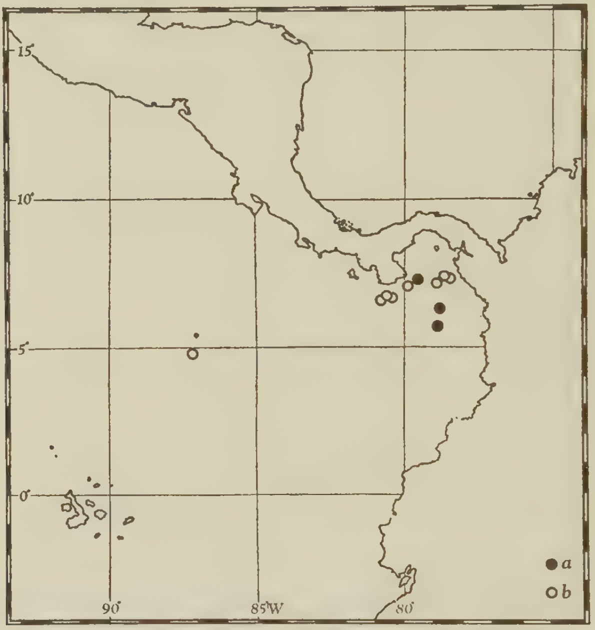

Figure 1. Distribution of *Borophryne apogon*. *a*, Galathea records; *b*, Earlier records.

Again, it was only when we arrived in the Panamanian regio that we met with *Borophryne*; the catch was seven females, one wit a parasitic male, and two free-living males; thus 10 specimens wer added to the 40 noted above (see Table I, Fig. 1).

The Ceratioid Fauna of the Gulf of Panama. In his thorough revisio of the ceratioid fishes, Bertelsen (1951) has ascertained that abou 650 specimens had been described previously, of which 392 wer taken on the Dana Expeditions; in his own study he added abou 100 metamorphosing or metamorphosed males and about 2400 larvae. Regarding ceratioids in general, he concluded (1951:223) "From the information available we may presume that *the majorit* *the Ceratioid species will be found distributed in all the oceans and at species hardly occur with a distribution restricted to the Atlantic cean.”*

But here the Panamanian region is a striking exception. Bertelsen 951:223) has written

> As pointed out earlier by R. and T. (1932, p. 13) a specially rich, both as to species and individuals, Ceratioid fauna was found by the “Dana” in the Gulf of Panama. This area has been investigated by 3 expeditions, and about 30 $^0/_0$ of all known Ceratioids in the metamorphosed condition have been collected there. Apart from doubtfully identified larvae, males and members of the previously mentioned groups of species, representatives of 30 species have been taken there and of these 14 are not known from other areas. 6 of these however are only known from single specimens and amount to no greater percentage of the catches than one would expect from a comparison with other areas. On the other hand, some of the remaining 8 species occur in such relatively large numbers . . . that this cannot be ascribed to chance. It is doubtfull, however, that the distribution of these species should actually be restricted to this narrow area. As will be noted in the following ecological section, we can find neither any natural barrier which might conceivably prevent a scattering of the larvae or older Ceratioids away from the area, nor special hydrographical conditions which might probably cause such a restricted distribution. It seems more probable that the special current conditions in the Gulf of Panama both horizontally and vertically have led to an accumulation of Ceratioids, which in other parts of their area of distribution are found so scattered that such a relatively large part of the species have not yet been observed elsewhere.

Regarding the distribution of ceratioid larvae in general relative o their environment, Bertelsen noted that the larvae are found nly within the temperature interval 11 to 29° C and that most, if ot all, species have at this stage their greatest frequency within the nterval 15 to 25° C. This means that the larvae live in the thermophere, above the thermocline.

This is in contrast to adult ceratioids in general, which live most ften in the psychrosphere, below the thermocline; as Bertelsen 1951:232) has stated: “. . . the frequency maximum most often alls in the layers where the temperature is between 4° and 5°.” This means that ceratioid adults in general are bathypelagic in the rue sense of the word. However, *Borophryne* is an exception to the ule for ceratioids in general, since a female with a parasitic male ttached was caught at 13° in the Gulf of Panama at a depth of nly about 200 m (Bertelsen, 1951:231).

Another remarkable feature of ceratioids is their ability to tolerate notably low amounts of oxygen, as Bertelsen (1951:233–234) has pointed out in his special analysis of this phenomenon in the Gulf of Panama. Suffice it to state here that the above mentioned female *Borophryne* with a parasitic male attached must have lived in water where the oxygen content was at most 0.1 ml/l, at a depth that is slightly less than that of the oxygen minimum (0.06 ml/l) for this station.

Stomias colubrinus

Like *B. apogon*, *S. colubrinus* Garman 1899 also has a peculiar pattern of distribution. The adults of this species probably live at much the same depths as those of *B. apogon*, in the psychrosphere, since practically all of the adolescents and adults were taken with 600 m wire or more. Also, the larvae probably live in the thermosphere, like those of *B. apogon*.

The Dana collections of the genus *Stomias* comprise 4879 specimens from all oceans. Ege (1934), who has given a detailed analysis of all of this material, has recognized six well defined species. Fig. 2 shows the distribution of *S. colubrinus*. Although only 210 specimens have been taken, it is safe to state that the species does not occur where bathypelagic fishing has been carried out except where shown in Fig. 2. For details, see Ege (1934).

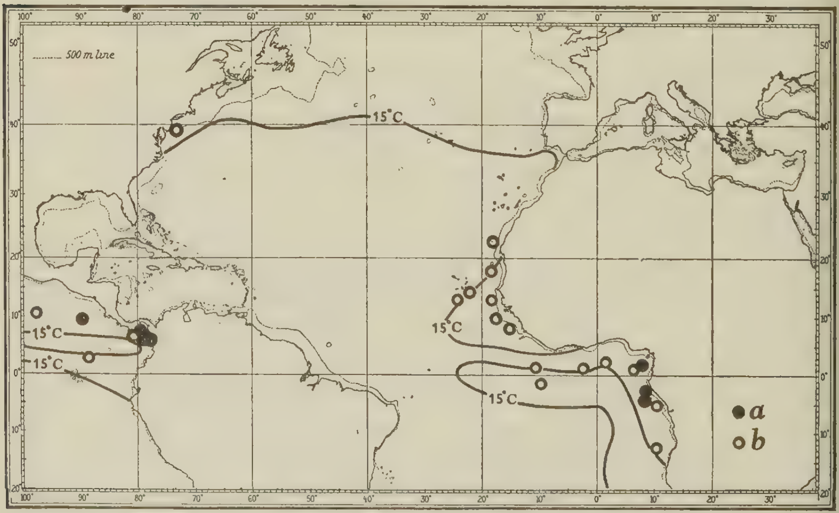

Figure 2. Distribution of *Stomias colubrinus*. *a*, Galathea records; *b*, Earlier records. Isotherms of 15° C at 100 m.

TABLE II. STOMIAS COLUBRINUS GARMAN COLLECTED BY THE GALATHEA

Sta.	*Date*	*Locality*	*Depth to Bottom (m)*	*Gear*	*Range of Catch (m)*	*No. of Specimens*	*Length (mm)*	
							Total	*Stand.*
52	30 November 1950	1°42′ N, 7°51′ E	2550	Shrimp otter-trawl	2550–0	1	68	65
—	—	—	—	—	—	1	178	168
65	4 December 1950	2°17′ S, 8°10′ E	2770	3 m sledge-trawl	2770–0	1	..	228
66	5 December 1950	4°00′ S, 8°25′ E	4020	3 m sledge-trawl	4020–0	1	..	96
—	—	—	—	—	—	1	..	103
716	6 May 1952	9°23′ N, 89° 32′W	3570	Open otter-trawl	3570–0	1	270	254
726	13 May 1952	5°49′ N, 78°52′ W	3270–3670	Open otter-trawl	3670–0	1	..	113
—	—	—	—	—	—	1	399	380
—	—	—	—	—	—	1	..	383
727	13 May 1952	6°26′ N, 78°43′ W	3570	Pelagic otter-trawl	1150–0	1	152	141
739	15 May 1952	7°22′ N, 79°32′ W	915–975	Open otter-trawl	975–0	1	..	c. 81
—	—	—	—	—	—	1	..	88
—	—	—	—	—	—	1	..	100
—	—	—	—	—	—	1	..	109
—	—	—	—	—	—	1	..	118
—	—	—	—	—	—	1	..	126

In the Gulf of Panama it has been recorded repeatedly ever sinc it was first described in 1889 from material taken on America expeditions. In 1922 it was caught by the DANA at the same station which yielded *Borophryne* for the first time, and when we found i again on the DANA Expedition in 1928, it was like greeting an ol friend. After we left the Panamanian region, for all our fishing, w did not encounter it again until we reached the West African regio where it had been taken by the DANA in 1921; here it had bee known since the German VALDIVIA Expedition recorded it in 1898

The GALATHEA, as mentioned earlier, circled the earth in the opposite direction from the DANA, so we met with *S. colubrinus* promptl in its previously known area of occurrence (Fig. 2, Table II). Thu we met with it first in the West African region, and only then unti we arrived in the Central American Pacific, where we collected i together with *Borophryne*.

The catch of a single specimen from the Hudson Gorge ma eventually fit into the pattern discussed, but more material fro this region is needed to determine whether or not it occurs ther regularly.

THE CROMWELL CURRENT

In 1954 Cromwell, *et al.* made a significant contribution whe they described the Pacific Equatorial Undercurrent, and in 195 Knauss and King, who have suggested that it be called the Cromwell Current following the untimely death of its discoverer, describe it thus:

> “The Undercurrent is an east-flowing current centred at the equato just below the west-flowing South Equatorial Current. Measurements a long. 140° W indicate a transport of the order of 30 million cubic metre a second or about the same as the transport of the Florida Current Measurements along the current indicate that it is at least 3500 miles long.‘

CONCLUSIONS

To most biogeographers, including myself (Bruun, 1936), it ha always been a puzzle how adult animal species remain in a restricte area, as in the case of *B. apogon* and *S. colubrinus*, particularly whe their larvae, living epipelagically, have apparently been carried fa from that area by surface currents. That a solution would be foun

correlating our knowledge of a species' life history with that
current systems seemed clear. In the recent discovery of the
mwell Current, physical oceanology has offered us what may
ve to be a key to the puzzle of the distribution of *B. apogon*
S. colubrinus, and probably of many other problems as well.
not probable that the larvae of *B. apogon*, at about the time
they are metamorphosing into adolescents, seek deeper layers
that the Cromwell Current may take them back to the Pacific
smanian region whence they came?

we know, there are some general similarities between West
an waters and corresponding tropical waters to the west of
ral America (*e. g.*, upwelling, abundant nutrients, food, etc.).
things considered, a biologist might postulate a current in the
antic similar to the Cromwell Current in the Pacific which would
vide an ecological set-up for *S. colubrinus* and other species of
Atlantic that is similar to that for *B. apogon*. Cromwell, *et al.*
54) have stated, "whether or not the current prevails in the
tern and western Pacific and in the Atlantic remains to be de-
mined by further study". Certainly much more detailed infor-
tion is required before a satisfactory picture incorporating all
tors can be developed and consummated.

have presented these striking examples of the distribution of
deep-sea species to demonstrate how much biologists need
re observations of the physical and chemical aspects of oceanol-
y, particularly from deep waters close to both West Africa and
ntral America, since they may be just as varied and complicated
surface waters (Brandhorst, 1958).

Thomas G. Thompson, my highly esteemed friend for many years,
been a great spirit in this field; may he still inspire many fol-
vers.

ACKNOWLEDGMENTS

The author gratefully acknowledges a grant from the Danish
ate Research Foundation, which made this study possible. Thanks
also due Mr. Kay W. Petersen, B.Sc., for his valuable assistance.

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SCRIPTION OF A PROTOTYPE GAUGE TO MEASURE MAGNI- E AND DIRECTION OF HYDROWIRE SLOPE *IN SITU* BE- EN REVERSING BOTTLES AT ALL DEPTHS AND UNDER ALL CONDITIONS OF SHIP DRIFT

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ABSTRACT

e discovery in recent years of vast deep oceanic currents running in a direction
ary to those at the surface provides additional evidence of our need for in-
ental means to obtain accurate data on subsurface waters, particularly in
known oceanic areas where pioneer lowerings are to be made. A description
ven of a prototype messenger-operated wire-angle gauge which, used inter-
ately between reversing bottles, can furnish information on the direction of
of the hydrowire and its actual degree of obliquity at a number of points. It
ly the latter, of course, which can be computed from results obtained when
otected reversing thermometers are used with the pressure-resisting type.

INTRODUCTION

ome years ago, after reading a number of papers, mainly theo-
cal, on the subject of wire angle in oceanography, the writer
ame convinced that there need be little difficulty in designing
imple instrument that would be usable between bottles of a
tine cast to reveal the actual slope of the hydrowire at as many
ts on it as weight tolerance might permit. Such an instrument,
rred to as a wire-angle gauge, was duly made and described
ruthers, *et al.*, 1954), and Lee's contribution to that paper tells
s practical use in the Barents Sea. Two forms of it were made,
messenger-operated; one was able to reveal slope magnitude
whereas the other could reveal both degree and azimuth of
rowire obliquity. Extensive use of our simpler nondirectional
of the gauge has been made from oceanographical survey
els of the Argentine Navy and a version of it has since been
ufactured by the French firm of Mécabolier. Subsequently
by (1955), whose 1957 paper is referred to in ours of 1954,

published a note evoked by E. E. Watson's criticism; Watso
paper is also mentioned in our 1954 publication. More recently t
writer's interest has been particularly aroused by a paper whi
not only describes a Japanese version of the simpler gauge b
which goes into some detail regarding the value of instrument
“depth determination in oceanographical observations” (Teramot
1958). This recent paper is well spiced with calculations.

So far as the writer is aware, that version of the wire-angle gau
which measured azimuth as well as obliquity has not been copie
This seems a little surprising because when a vessel has had
approach the hydrowire to achieve virtual verticality of its upp
most portion, it is surely of great interest to learn what the directi
of “carry-away” down below must have been if it later becom
known thermometrically that there had been a considerable w
angle in the depths. Much information regarding the direction
deep currents could easily be obtained from use of messeng
operated gauges of the directional variety. Used in the Barents S
from the F.R.V. Ernest Holt which cannot be steamed up to t
hydrowire, one of the directional wire-angle gauges showed I
that at some places “the bottom water was moving in a differe
direction to the surface water”.

The writer has recently given further attention to his gaug
because of the great present-day interest in deep currents. It w
found that the two instruments described and illustrated in t
1954 paper could be much improved. When used from a ship maki
only slow leeway, the previously-described instruments can be e
pected to give acceptable results because, in such cases, they w
remain truly pendulous beneath the wire as they must to provi
satisfactory data. Because their pendulums are heavy, howev
there is some possibility that, even when truly pendulous, towar
and from-ship oscillations might on occasion be great enough
cause error. This could happen if the messenger should strike wh
the pendulum was not at its modal inclination with the frame
the gauge.

Furthermore, if these same instruments are used from a ves
drifting briskly to leeward, error is certain because such flat-fram
instruments cannot then remain truly pendulous beneath the w
in defiance of water pressure upon them. They will lift to the s
of the wire or perhaps even ride above it if ship drift is fast enou
Thus the recorded angle will be much in defect of truth–perh

. Because of these considerations the gauge has been completely
signed and has been given certain internal rolling features similar
he writer's jelly cylinder slope indicators made for use on trawl
ps and other towed cables which are described elsewhere.

e redesigned hydrowire slope gauge remains messenger-operated
usable between bottles of a routine cast, but only the obliquity-
azimuth variety has been produced anew. The main feature
e new directional wire-angle gauge is that it behaves correctly
ther it be pendulous beneath the wire when leeway is small or
e side or above the wire when the ship is drifting briskly down-
. There is no call here for a long and detailed description be-
e we are here dealing exclusively with the prototype instrument
e largely in the workshops of the British National Institute of
anography. The manufacture of a sales version of it incorporating
ous desirable modifications (one of them being greatly decreased
ght), has been confided to the Norwegian firm of Bergen-Nautik.
refore, for present purposes, the accompanying photographs
suffice.

he new instrument, which is cylindrical, naturally operates like
eversing water bottle in that, after having been operated by
ssenger impact from above, it releases a second messenger to
another bottle or gauge below it. The prototype weighs eight
nds. In a casing of perspex tubing $8^{1}/_{2}$ inches in length, 4 inches
utside diameter, and with wall thickness of $^{1}/_{4}$ inch is a skeleton
angular metal frame which turns on two end bearings which
central in the inner sides of the two brass discs which close the
e. At the lower end of the instrument, the bearing is virtually
ivot turning in a seating made of ferobestos, which is especially
able for use under water; ferobestos is an asbestos fibre material
regnated with a special thermo-setting synthetic resin which
rds a sort of self-lubrication. At the upper end, inside of the
spex cylinder, the frame turns round a tube through which a
on enters. Mounted on an axis pivoted across the frame is a
el of tufnol that is a trifle less in diameter than is the internal
meter of the perspex cylinder. A quadrant of this is engraved
degrees, and within it is a cut-away portion which houses a
ly-pivoted compass (see accompanying photographs).

he perspex cylinder has strong metal ends furnished with the
essary clamps for attachment on the hydrowire. The upper end
ries the tripping lever as well as a release point from which hangs

a lanyard supporting the pass-on messenger. When the messeng
from above trips the gauge, the spring-loaded piston seen in th
pictures travels inwards to press a rubber pad against the finel
serrated rim of the graduated tufnol wheel; in doing so it locks th
latter effectively so far as angle of slope is concerned. That is no
the end of the piston's duty however. After the rubber pad ha
pressed on the wheel, a small spike emerges from its centre to sta
into a cavity milled round the rim of the wheel. In this cavity
a snug-fitting arc of thin brass so pivoted that inwards pressure
the spike at any point on the graduated rim rocks a pair of ligh
L-shaped levers (one on each side of the wheel) in such mann
that they lift the compass off its pivot to jam it tightly but harm
lessly up against a cylindrical block of tufnol (integral with th
wheel). A weight is affixed to the rim of the wheel below the com
pass to ensure that the compass is always at bottom vertically b
low the midpoint of the wheel's axis. This weight, which is of lea
is heavy enough to turn the wheel so resolutely that it will alwa
accord correctly with the slope of the gauge. The lead strip is
distributed as to weight that, when the cocked gauge is vertica
the compass is on an even keel at bottom with its pivot in line wi
the axis of the piston. In that position the zero mark on the gra
uated quadrant is against a line scribed round the inside of th
perspex cylinder for easy and parallax-free angle reading. Fro
the photographs the reader will now be able to make out for hi
self how the gauge behaves in use. No matter what position th
untripped gauge may take on the wire due to water pressure o
casioned by ship drift, the internal mechanism rolls accommoda
ingly in such manner that the graduated tufnol wheel remains
ways vertical. That being so, the compass remains always horizont
and perfectly free to turn on its pivot until such time as the me
senger strikes from above. The rolling of the rectangular frame
greatly assisted by the caged ball seen in the picture. This is a sol
phosphor-bronze sphere $1^1/_4$ inches in diameter.

Apart from incorporation of this rolling ball and a few rece
modifications of the compass-locking levers, the gauge here describ
and photographed is just as it was when it was used from t
F.R.V. ERNEST HOLT during an Arctic cruise in May 1958. On th
cruise it was useful to learn reliably that small wire angles exist
near the bottom of a deep cast at times when the uppermost porti
of the wire was sloped at 40° and more.

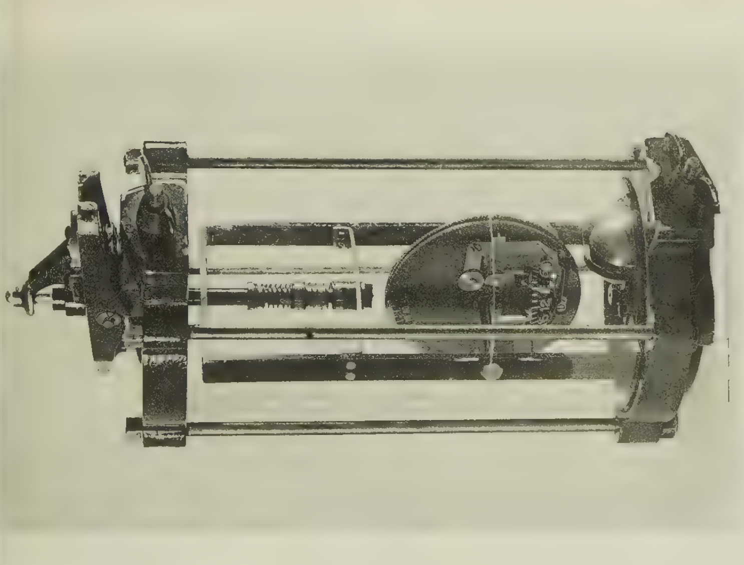

Figure 1. Showing the entire gauge in the cocked position. [Angles are read against the line scribed round the inside of the cylinder.]

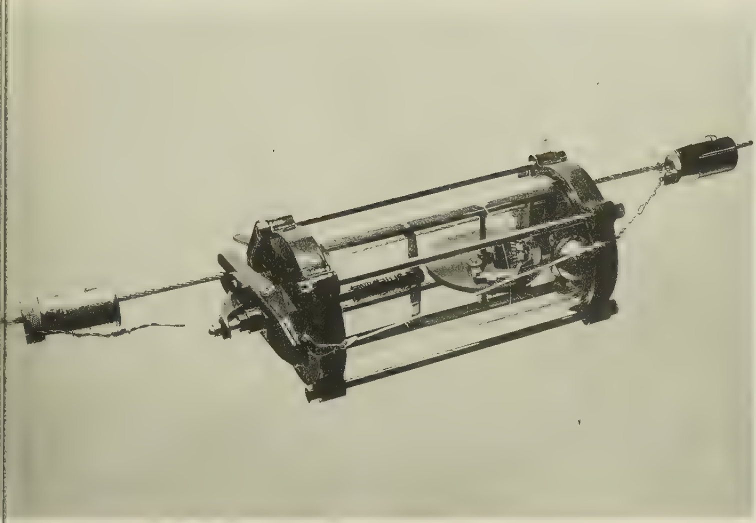

Figure 2. Showing the cocked gauge on the hydrowire ready to receive the messenger from above and to release one beneath.

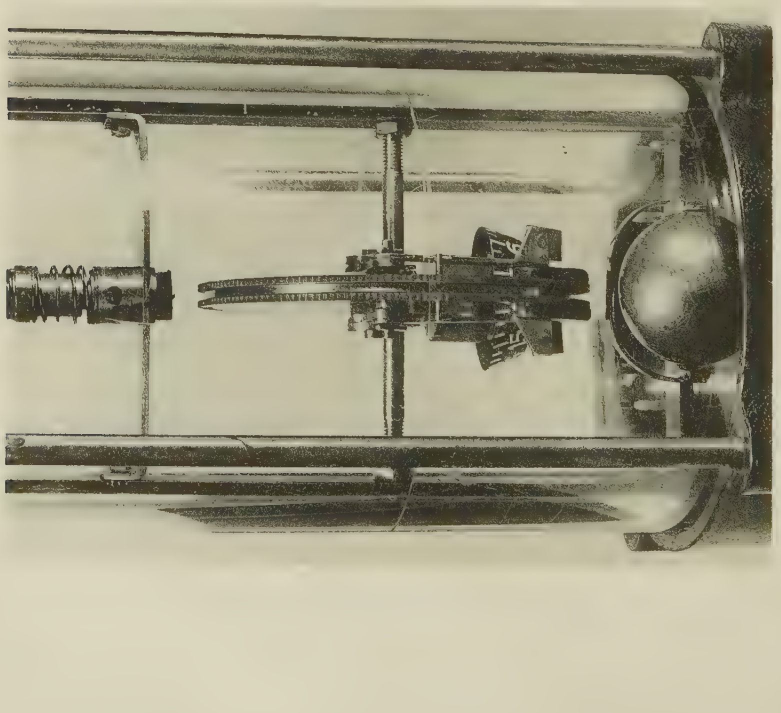

Figure 3. A close-up view of the internal parts. [Gauge cocked.]

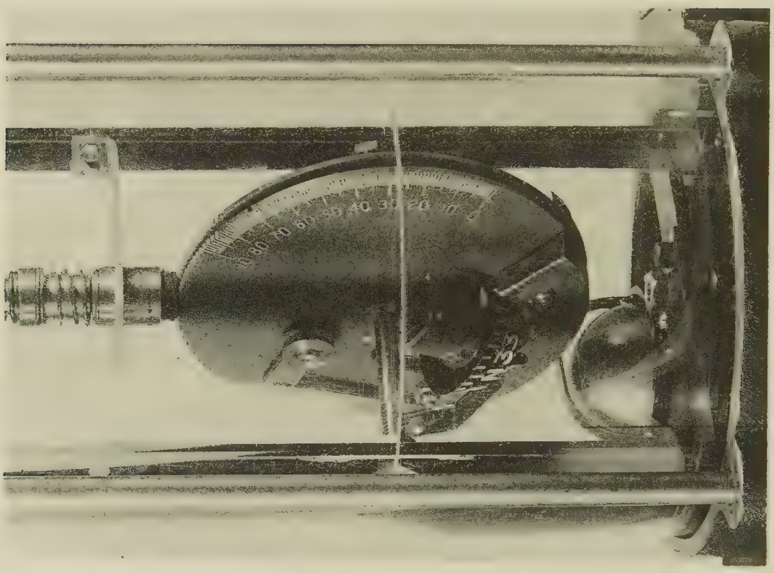

Figure 4. Close-up view showing protractor wheel and compass locked as when removed from the hydrowire.

The illustrations are numbered in sequence in the usual manner hough they have not been referred to individually. This has been e for the convenience of any reader who might wish to send in inquiry about any part of the gauge.

ACKNOWLEDGMENTS

The writer is greatly indebted to his colleague, Mr. J. T. R. Wood, the exercise of much painstaking skill in constructing the inter- mechanism of this directional wire-angle gauge. Initially, when piston had only one movement, the compass could not be locked hout the wheel turning enough to falsify the slope angle recorded. recessing the rim of the wheel and fitting into it the curved er operated by the second movement of the piston as described, Wood solved the difficulty. Moreover, besides devising and con- ucting the compass-locking mechanism, to him also goes credit the caged ball which rolls the rectangular frame. For the photo- phs of the gauge the writer tenders thanks to his colleague Mr. F. Magdwick.

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LEAD ISOTOPES IN SEA WATER AND MARINE SEDIMENTS

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ABSTRACT

The lead concentration obtained from sea water samples of San Juan Channe Washington was 0.2 μg/l or less. Leads isolated from Pacific and Atlantic pelag clay sediments show an isotopic composition similar to that of manganese nodul from the respective oceans. The Pb^{206} content in the Atlantic lead was more abunda than that in the Pacific lead. This finding agrees with the postulate that the Atlant lead was derived from rocks which contained high proportions of old granites an that the Pacific lead was from rocks containing high proportions of relativel young basalts.

INTRODUCTION

Lead isotopes in ores and in igneous minerals have been the ob ject of intensive investigation inasmuch as they are the end proc ucts of three major radioactive decay schemes used in determinin geologic ages. The pelagic sediments deposited in oceanic basir have been derived principally from weathering of rocks on a continents (Landergren, 1956), and it is considered that the isotopi composition of the leads in these sediments represent the averag composition of lead in the crust of the earth (Patterson, *et al* 1953). Wickman (1948) has suggested that lead isotope ratios coul be used as a basis for determining the age of certain marine sed ments. Thus studies of lead isotopes in oceans, which serve as mixin reservoirs and sedimentation media, can provide important know ledge relating igneous and sedimentary rocks.

An authoritative discussion on the geochemistry of Pacific pelag sediments has been presented by Goldberg and Arrhenius (1958 The present investigation was undertaken as a preliminary surve to determine the isotopic composition of leads in Pacific and Atlant

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[1] Contribution No. 905, Division of Geological Sciences, California Institute Technology, Pasadena, California.

gic sediments and to ascertain whether or not there are correl- ns between the concentration of lead and of other trace elements he sediments.

METHODS AND SAMPLES

chemicals used in this investigation were analytical grade and further purified to minimize lead contamination. The mass trometer was a 60° sector, single-focussing instrument with a ch radius of curvature and a surface ionization source. A de- d description of the mass spectrometric and chemical proced- has been given by Chow and McKinney (1958). The lead con- ration of sea water and sediments was determined by the iso- dilution method, with Pb^{206}-enriched lead solution as the er. The iron determination was carried out by reduction of the c iron in a silver reductor and by titration with a standard romate solution. Other minor and trace elements in sediments determined by using the emission spectro-chemical method, quartz as the diluent. A copper target X-ray diffractometer used in identifying the minerals in the sediments.

he two Pacific pelagic clay cores, provided by Dr. E. D. Gold- of the Scripps Institution of Oceanography, were collected at . 35°09′ N, Long. 157°17′ W (Chinook-2) and at Lat. 43°16′ N, g. 163°40′ W (Chinook-5). The Chinook-2 core was 54 cm long; Chinook-5, 84 cm. There were no age-indicating fossils in these s.

he Atlantic core (A-160-1), made available by Dr. D. B. Ericson he Lamont Geological Observatory of Columbia University, was en at Lat. 30°08′ N, Long. 57°63′ W; it was 364 cm long and tained a brown clay of the Pleistocene age.

Vater samples in San Juan Channel, Washington (Lat. 48°36′ N, g. 123°04′ W) were obtained from the surface down to 100 m at n intervals, using a nonmetallic water sampler (Thompson and w, 1955a) and polyethylene containers for storage of the samples. Pb^{206} tracer solution was added immediately to 5 l of untreated er; the equilibration time of the tracer with the sample varied n two hours to seven days. The lead was then recovered by izone extraction; final purification and analyses of the lead e performed at the California Institute of Technology.

DISCUSSION AND RESULTS

Lead in Sea Water. Results of analyses of sea water in San Jua Channel showed a lead concentration of 0.1–0.2 μg/l (Table while results of previous analyses, tabulated by Richards (1957 have ranged from 2–8 μg/l. It is quite probable that the high lea concentration reported by many investigators has been due contamination of samples, to improper analytical technique, both. The analytical procedures of previous observers involved t concentration of sea water by evaporation, separation of the lea by coprecipitation and then spectroscopic analysis. It is importa to note that any equipment which has been coated, plated or paint with protective substances containing lead is unreliable for taki samples on which lead is to be determined.

TABLE I. Lead Concentration in the Waters of San Juan Channel, Washington (Lat. 48°36′ N, Long. 123°04′ W) in August 1956

Date	*Location*	*Depth (m)*	*Chlorinity (°/₀₀)*	*Lead (μg/l)*
August 2	Off observation pier	0	16.66	0.20
August 4	Off observation pier	0	16.70	0.18
August 8	Midchannel	0	16.73	0.10
August 13	Midchannel	25	16.58	0.22
August 13	Midchannel	50	16.73	0.14
August 13	Midchannel	75	16.68	0.12
August 13	Midchannel	100	16.79	0.17
August 22	Off Jones Island	25	16.78	0.07
August 22	Off Jones Island	50	16.84	0.07
August 22	Off Jones Island	75	16.99	0.15
August 22	Off Jones Island	100	17.18	0.11

Trace Elements in Sediments. Results of spectrochemical analys of Pacific and Atlantic pelagic clay sediments are given in Tabl II, III and IV respectively. The Chinook-2 core showed a distin discontinuity in its chemical composition at a depth of 22 cm belo the surface; in the upper part of the core the concentrations of tra elements remained relatively constant, but in the lower part the increased two- to four-fold with the exception of barium, titaniu and chromium, whose concentrations showed a reverse trend. T average concentrations of trace elements were comparable to tho reported by Goldberg and Arrhenius (1958). Phillipsite was fou

TABLE II. PARTIAL CHEMICAL COMPOSITION OF THE PACIFIC PELAGIC CORE CHINOOK-2 (SCRIPPS)

Depth Below	*Fe*	*Mn*	*Ca*	*Sr*	*Ba*	*Pb*	*Co*	*Cu*	*Ni*	*B*	*Ti*	*Zr*	*V*	*Cr*	*Y*	*Yb*
Surface, cm	(%)	(%)	(%)	*ppm*												
0– 4	3.2	0.40	0.80	38	3,000	25	47	300	110	300	8,000	350	40	70	tr.	5
4– 8	3.3	0.37	0.65	20	2,000	25	40	270	100	300	6,900	350	30	55	tr.	5
8–12	2.5	0.40	0.68	27	2,000	26	44	280	100	300	6,800	350	40	55	tr.	6
12–16	3.1	0.49	0.74	32	2,000	26	60	300	150	290	7,300	350	30	55	60	7
16–20	3.2	0.65	0.80	20	2,000	30	85	270	180	290	7,500	350	30	55	75	9
20–22	3.4	0.81	0.82	30	2,000	37	85	290	180	270	6,800	300	30	50	100	11
22–25	2.3	1.4	0.83	25	1,000	51	120	280	340	180	3,000	270	25	18	100	10
25–28	3.3	1.8	1.5	45	1,300	59	250	310	380	260	5,000	450	40	22	250	20
28–31	3.0	1.6	2.0	70	1,400	56	230	340	350	300	5,600	480	55	24	250	20
31–35	4.3	2.5	2.5	70	1,000	99	230	500	520	240	3,200	380	50	18	580	40
35–39	8.3	2.6	2.8	65	1,000	122	200	600	550	260	3,100	450	110	20	550	40
39–43	9.8	2.3	2.8	75	900	102	130	640	500	250	2,600	500	100	16	580	40
43–47	10.6	2.4	2.6	95	1,200	124	120	660	400	250	3,000	500	180	16	540	36
47–51	12.2	2.5	2.2	100	1,100	130	120	740	500	270	2,800	500	200	15	420	38
51–54	11.9	2.4	2.2	100	1,200	127	90	600	400	250	2,800	480	180	15	430	33

at the discontinuity zone of Chinook-2; it was identified by con paring its X-ray powder pattern with that of phillipsite from Sten pel near Marburg, Germany (Lippmann, 1958).

TABLE III. Partial Chemical Composition of the Pacific Pelagic Co
Chinook-5 (Scripps)

Depth Below Surface, cm	*Fe* (%)	*Mn* (%)	*Ca* (%)	*Sr* ppm	*Ba* ppm	*Pb* ppm	*Co* ppm	*Cu* ppm	*Ni* ppm	*B* ppm	*Ti* ppm	*Zr* ppm	*V* ppm
10–12	3.3	0.26	1.0	60	1,800	25	30	200	60	160	3,800	180	30
20–24	3.8	0.38	1.1	70	1,800	26	45	240	85	200	5,600	250	35
32–36	3.7	0.32	1.2	70	2,000	25	40	250	80	200	7,300	320	25
44–48	3.7	0.38	1.5	75	2,300	24	40	250	75	210	6,800	260	25
56–60	3.9	0.30	1.1	70	2,000	26	45	260	80	200	7,200	310	30
68–72	3.9	0.41	1.1	100	3,800	31	50	280	100	210	6,800	340	35
80–84	4.1	0.57	1.0	75	3,400	35	50	350	165	230	7,100	320	30

The chemical composition of Chinook-5 was similar to that of tl upper part of Chinook-2. It is assumed that sediments in the ar of Chinook-5 were thicker than those of Chinook-2 and that tl Chinook-5 core did not penetrate into the discontinuity zone.

TABLE IV. Partial Chemical Composition of the Atlantic Pelagic Co
A–160–1 (Lamont)

Depth Below Surface, cm	*Fe* (%)	*Mn* (%)	*Ca* (%)	*Sr* ppm	*Ba* ppm	*Pb* ppm	*Co* ppm	*Cu* ppm	*Ni* ppm	*B* ppm	*Ti* ppm	*Zr* ppm	*V* ppm
0– 4	1.5	0.58	7.2	180	620	35	48	210	110	200	4,800	200	50
48– 52	1.4	0.58	5.2	120	780	28	52	210	100	240	6,000	220	50
98–102	2.9	0.72	7.8	220	640	30	75	190	140	220	5,500	240	55
148–152	2.5	0.77	0.81	25	720	34	70	190	120	250	5,500	230	50
198–202	2.2	0.86	0.70	25	780	34	76	180	110	260	5,500	250	50
248–252	2.3	0.80	0.74	25	720	45	80	140	110	260	5,500	240	55
278–282	2.4	0.90	0.82	20	790	32	82	150	120	280	5,500	260	50
308–312	2.2	0.98	0.70	20	680	36	82	170	130	280	5,200	250	50
360–364	3.0	0.95	0.74	20	670	38	82	160	140	290	5,300	240	50

On a carbonate-free basis, trace elements of the Atlantic co were also comparable to those of the upper section of Chinook- Excess amounts of calcium and strontium in the top 100-cm sectic of the Atlantic core were due partly to biological activities.

The average strontium-calcium atom ratios were 1.5×10^{-3} to $\times 10^{-3}$ for the Pacific sediments examined, 1.7×10^{-3} for the antic sediments, and, according to Thompson and Chow (1955b), $\times 10^{-3}$ for the Pacific globigerina ooze.

ead Isotopes in Sediments. Various sections of the three cores re analysed to determine their isotopic composition and lead centration. Leads were isolated from sediments by hydrochloric d extraction. Results of these analyses are given in Table V. e lead concentration of Chinook-2 increased with increasing depth ile that of the Atlantic core remained rather constant although length was seven times that of Chinook-2. The lead concentration the sediments was proportional to that of manganese.

The isotopic composition of lead in the Pacific cores was considered iform within the assigned error. The lead isolated from the upper

TABLE V. Isopopic Composition of Lead in pelagic Sediments

pecimen	*Depth Below Surface, cm*	*Concn. Pb, ppm*	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{206}}{Pb^{207}}$	$\frac{Pb^{206}}{Pb^{208}}$
cific Ocean	4– 8	25	18.837	1.1910	0.4792
re Chinook-2	16– 20	30	18.815	1.1921	0.4779
t. 35°09′ N	22– 25	51	18.789	1.1921	0.4792
ng. 157°17′ W	28– 31	56	18.861	1.1912	0.4794
pth 5,600 m	35– 39	122	18.780	1.1900	0.4786
	43– 47	124	18.847	1.1906	0.4795
	47– 51	130	18.867	1.1903	0.4812
cific Ocean	10– 12	25	18.860	1.1909	0.4792
re Chinook-5	20– 24	26	18.795	1.1922	0.4788
t. 43°16′ N	44– 48	24	18.797	1.1923	0.4794
ng. 163°40′ W	68– 72	31	18.807	1.1913	0.4790
pth 4,170 m	80– 84	35	18.839	1.1914	0.4795
jacent Pacific Nodules		2,000	18.810	1.1908	0.4783
lantic Ocean	48– 52	28	19.201	1.2133	0.4818
re A–160–1	95 (nodule)	1,020	19.204	1.2101	0.4832
t. 30°08′ N	98–102	30	19.175	1.2107	0.4813
ng. 57°53′ W	148–152	34	19.107	1.2070	0.4825
pth 5,090 m	198–202	34	19.046	1.2034	0.4825
	248–252	45	19.073	1.2021	0.4807
	278–282	32	19.073	1.2070	0.4821
	308–312	36	19.155	1.2048	0.4824
	360–364	38	19.102	1.2066	0.4817

100-cm section of Atlantic core A-160-1 showed a slight differenc in isotopic composition as compared with the lead below 100 cn The difference, considered significant, might reflect the characte istics of various deep water masses overlying the sediments in tl past. It should be noted that appreciable amounts of calcitic test were also found in the upper 100-cm stratum of the core.

Pacific sediments revealed that the lead had approximately th same average isotopic composition as adjacent manganese nodule The manganese nodule found inside Atlantic core A-160-1 showe by analysis the same isotopic composition of lead as its surroundin clay sediments. The resemblance in isotopic composition of lea between sediments and manganese nodules is important for futu study of marine leads since sediments are more accessible tha manganese nodules.

For interocean comparison, the pelagic sediments demonstrate the same trend as the manganese nodules in that the Atlantic lea contained more Pb^{206} than the Pacific lead. This finding is in agre ment with the postulate (Chow and Patterson, 1957, 1959) th Atlantic lead was derived from rocks which contained high propo tions of old granites while Pacific lead came from rocks containin high proportions of relatively young basalts.

ACKNOWLEDGMENT

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A SYSTEM FOR INTERNATIONAL EXCHANGE OF SAMPLES FOR TRACE ELEMENT ANALYSIS OF OCEAN WATER

By

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ABSTRACT

The hazards inherent in sampling at sea for trace element analyses are discussed. It is proposed that a discussion be held at Helsinki in 1960 on:—

(a) sampling for trace element analysis;

(b) a system for international exchange of samples and for reciprocal control of methods for analysis of trace elements.

INTRODUCTION

For many of the elements present in the sea in trace amounts, it is difficult to glean from the literature any firm idea of the amounts truly present in the ocean (Goldberg, private communication; Richards, 1956[1]). For some elements the reports from different analysts vary by several orders of magnitude. Elements taking part in the biological cycle have naturally a wide range of concentrations in the more accessible shallow waters, where they are often poorer than in the deep ocean reservoirs. Also, the deep Atlantic, due to its more vigorous vertical circulation, is often notably poorer than the deep Pacific.

In greater part, however, discrepancies arise from contamination, often gross, of the samples.

We need a measure of the mean content of trace elements and of trace organic constituents of the ocean. Such information cannot be had without sampling the deep oceans. We also need reliable measures of the way in which distribution varies from place to place or from time to time due to biochemical, physico-chemical, or geochemical processes. It is essential to be able to compare confidently the results of many analysts in many laboratories using methods which, from the nature of the problem, do not admit of standardization at the present time.

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[1] F. A. Richards, 1956. On the state of our knowledge of trace elements in the ocean. Geochim. Cosmochim. Acta, *10*: 241–243.

It is practical to arrange a supply of "standard sea water" for determinations which are made in quantity and which satisfy other exacting requirements, as for determinations of chlorinity. Abundance of analyses and consequent cross checking enables us also to have reasonable confidence in figures for the distribution of phosphate, silicate, nitrite and oxygen. For all other trace constituents, the only practicable check seems to be through encouragement of an exchange of samples between analysts who have the means of collection at hand and who are aware of the need for accuracy.

Faults in Technique. Shortcomings of standard oceanographic apparatus and techniques for collecting samples at sea for trace analyses are:–

(a) Contamination of a sample by material from the sampling gear, which is often made from an alloy of copper, possibly electroplated. Copper and elements of its numerous alloys as well as elements used in electroplating or anodizing are ever-likely contaminants.

(b) Contamination of a sample by the patina which may accumulate on collecting and storage bottles or by organic coatings. Iron and elements which co-precipitate with ferric hydroxide may be introduced in this way.

(c) Contamination by rust from the steel wire which supports the bottle. Although iron and zinc are the most likely contaminants from this source, today many elements are alloyed into steel.

(d) Contamination from the bottle in which a sample may be stored, or loss by adsorption of constituents from the sample onto the surface of the container. Contamination varies with the nature of the bottle. Glass may be very treacherous, and although polythene seems to be ideal for short-time storage of samples intended for silicate analysis, it has not been established unreservedly that it is suitable for everything; not only is it permeable to water, but it seems liable to absorb or adsorb material from one sample and to give it back to later ones.

(e) Contamination from materials in rubber washers and stoppers. This has been given little thought. Antimony sulphide is used less often now than it used to be in compounding rubber, but the number of contaminants which may leach out of commercial vulcanized rubber was and remains legion. Neoprene should be considered.

(f) Contamination on board ship from the hands of the operators At sea it is more difficult to keep the hands clean than in a shor laboratory. Rust and grease are the worst offenders when worl has to be carried on from a small ship in poor weather.

(g) Contamination by smoke and ash from smoke-stacks, galle chimneys, or a lighted cigarette to windward, and from sewag and waste of all kinds discharged from the ship during sampling Rarely are these hazards sufficiently appreciated.

(h) Presence or concentration of an element sought in or upo either living organisms or non-living detritus in the sampled wate can hardly be called contamination, but it may cause annoyin lack of agreement between replicate samples.

It will be appreciated that the standards maintained for the collection of samples for analyses of chlorinity and oxygen, thoug stringent, fall short of what should be demanded by a trace analyst It is quite unreasonable for an analytical chemist to ask a physica oceanographer, pursuing other ends, to collect samples accordin to the exacting demands which the analyst ought to insist upon Chemists must collect their own samples and must work togethe internationally to obtain and exchange samples of known history furthermore, they must, in mutual interest, be prepared to undertak preliminary work at sea, such as filtration.

Necessary Advances. Steps to overcome these sources of error wil differ according to the trace constituent under examination, *e.g.* iron and copper behave quite differently as contaminants. In general non-metallic gear should be used so far as possible for collecting samples for metal analyses. A number of laboratories have now constructed closing bottles in polythene. Although many will not have the resources to use a complete "hydrographic wire" made of nylon or terylene, an extension of 50 m or so of such material, to be worked below a steel wire at any depth, is possible.

For storage, the choice at present seems to rest between glass, polythene (polyethylene and now polypropylene) and other plastics. It would seem wise, if possible, to avoid spring stoppered, screw-stoppered, or ground-glass stoppered bottles. Ideally, glass bottles intended for storage of samples for analyses of trace elements should be made from sand, soda, lime, and maybe borax, of Analytical Reagent quality or better. A commercial firm, prepared to execute a trifling order to such a stringent specification, would be

rd to find. Is the need by chemical oceanographers sufficient for
n approach to a glass industry research association (or similar
ody) to devise specifications and to manufacture a few gross bottles?
Again, is there a case for glass or polythene phials with narrow
ecks which, after filling, may be at once sealed on board with a
low-pipe flame? With canisters of Calor-gas or hydrogen, such a
low-pipe is practicable on any ship. Transport of such sealed samples
y land, sea or air would then be easy and free from risk of con-
mination or leakage during transit.

Standard Stations. For work such as this the Plymouth Labora-
ry has established a standard station in the Bay of Biscay at
at. 46°30′ N, Long. 8°00′ W, in 4710 m depth. Samples to the
ottom have been drawn for a number of British Laboratories for
recision analyses of chlorinity, oxygen, phosphate, total phospho-
rus, silicate, arsenic, rubidium, caesium, iron, copper, strontium,
allium, germanium, cadmium, gold, uranium and vitamin B_{12};
euterium is being analysed in the United States. Eventually we
hall have a considerable store of information for comparison with
eterminations elsewhere and with further information which will
e collected at the same position in the future. We are prepared,
ithin our resources and at our own convenience, to collect similar
amples (not exceeding one litre, or five litres exceptionally) for
nalysts elsewhere. The recipients of such samples would be ex-
pected to bear the expense of bottles and transportation.

The conditions of a general expedition, with a tight programme
f varied work and diverse interests, rarely encourage the sacrifice
f time which sampling for trace analyses demands. In my opinion,
t is better and much easier to obtain optimal conditions for sampling
race elements on a short economical excursion designed for this
purpose alone and with a chemist in charge.

It seems that chemical oceanography would be best advanced
by choosing carefully a few standard stations, widely spread over
he world, where pioneer work would be concentrated and from
which samples would be distributed on an exchange basis. Such
tations, in depths preferably exceeding 4000 m, would be as close
s convenient to laboratories devoted to chemical oceanography.
Excursions to these stations would be in charge of analytical chemists
who would have similar standards of accuracy and achievement and
who will have learned to trust experienced colleagues operating

similar stations in other waters. Mutual confidence is essential. No until methods had been well proved under the most favourab conditions would they be employed on general expeditions wit varied programmes and severe competition for available time an gear.

Isolated analysts and geochemists interested in the sea shoul be encouraged to use such a tested service to obtain the sample they need. They could, with advantage, be encouraged to partic pate in order to learn for themselves how to overcome the difficu ties normally encountered in trace element work.

International Co-operation. Many independent analysts, and othe at small marine laboratories, may find themselves unable to provid suitable sample containers or to defray considerable carriage charge

An international body seems necessary:–

(a) To encourage oceanographic laboratories to collect samples fo exchange according to the stringent standards of chemical clear liness which are necessary.
(b) To specify such standards and to concentrate efforts in skille hands.
(c) To encourage the design, manufacture and distribution o suitable sample containers.
(d) To place analytical chemists and geochemists in need of sample in contact with those who can get them.
(e) To obtain funds to defray costs of carriage and containers.
(f) To arrange smooth passage through customs.
(g) To arrange for re-use of containers on a "common-user" basis, a railway managements operate freight trucks. This would avoid th costly transport of numbers of "returned empties" about the worl

The Committee on Chemical Oceanography appointed by th International Association of Physical Oceanography at Toronto i September 1957, with myself as Chairman, is an international bod which might consider undertaking this work.

Therefore it is proposed that a discussion should take place durin the meeting of the International Association of Physical Oceanog raphy at Helsinki in 1960, embracing the following subjects:–

"Sampling for trace element analysis" and "A system for inte national exchange of samples and for reciprocal control of method for analysis of trace elements".

WAVE PATTERNS OFF SOUTHERN CALIFORNIA[1]

By

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ABSTRACT

apping of wave trains during four flights over the ocean off southern California ed the consistent presence of a high 10-second swell from the westnorthwest, ne or two low 3- to 5-second swells from other westerly directions, and of local d waves; occasionally a low 13-second swell from the west and southwest was present. Islands reduce the height of swells but produce little discernable cross- ll in their lee. Maps of swells and wind waves provide information on the best rses to be followed by airplanes during ditching at sea; they may also aid in interpretation of wave recordings at shore stations. The direction of most swells uch as to drive the sand of mainland beaches to the southeast in general, ac- ding with the known chief direction of accumulation of sand against artificial ch structures.

INTRODUCTION

Charts showing the direction of movement of ocean waves were de and used for navigational purposes by the Marshall Islanders til the end of the nineteenth century. Such charts were constructed split palm stems arranged in a frame, on which were fixed shells denote islands and short parallel sticks to represent swells. Ex- ples of the charts and a summary description of them have been ven by Emery, *et al.* (1954; 4, 5, pl. 1). Made by acute observers nature, these charts represent a form of wave study that has not en investigated by modern man with his array of elaborate in- uments. Instead, recent work on ocean waves has been directed ostly toward studies of refraction in local areas of shallow water unk and Traylor, 1947), of the spectrum of wave heights measured shore stations (Munk, 1947) and computed from weather maps aur, *et al.*, 1947), and of the influence of waves on natural (Munk d Sargent, 1948) or artificial (Fleming and Bates, 1951) structures.

In order to learn whether an improvement might be made over lynesian techniques and to determine the wave pattern existing off southern California, the writer made wave observations aboa the University of Southern California's R/V VELERO IV during cruis that were set up mainly for other purposes. Azimuths of two more sets of wave trains were noted both visually and on a rad scope. It was soon learned, however, that wind and wave conditio in this region vary too rapidly to permit mapping of waves duri the several days that are required to cover the area by ship.

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[1] Allan Hancock Foundation Contribution No. 230.

Observation from an airplane was obviously required. Throu the interest of the Office of Naval Research, facilities were ma available by Fleet Air Wing Fourteen, Naval Air Station, Nor Island, San Diego. Four flights were made at three-month interva on 15 October 1957, 16 January, 15 April, and 15 July 1958, usi the Marlin (P5M) seaplane for three flights and the Neptune (P2 amphibious plane for one. The high degree of visibility from t latter made it ideal for the work. Excellent co-operation was pr vided by administrative and flight personnel. Appreciation is al due D. S. Gorsline, R. L. Dunbar, E. S. Roth, and R. E. Stevenso students of marine geology at University of Southern Californ each of whom acted as recorder on one or more flights.

METHOD

Flight lines totalling 720 to 910 statute miles were covered 4 to 6 hours; differences between the four flight plans came abo because of military restrictions (imposed by Point Mugu Missi Test Center) and because of a desire on the second flight to foll a closely spaced grid. Positions were obtained by radar fixes 15- to 30-minute intervals. Since flights had to be scheduled a we or two in advance, no selection of weather was possible; howev each flight happened to occur on a day of typical weather wi northwesterly winds of 10 to 20 miles per hour in all of the regi except near the northwestern corner of the survey, where win were 20 to 30 miles per hour.

After some experimentation, an elevation of 2000 feet was s lected as most suitable for identifying separate wave trains; c servation at lower elevations caused some confusion by too gre detail, and at much higher elevations trains of small waves tend to be overlooked. Owing to low clouds, the fourth flight was ma at only 400 feet.

Observation was purely visual and was found to be clearest wh

ave trains were viewed away from the sun at an angle of about
° from their crest azimuth and at a downward angle of 15 to
°. This angle of view permitted identification of waves by the
ernation of dark and light stripes at the near and far sides of
ve crests produced by differences in the ratio of light coming
m within the water and reflected from its surface. Cross-checks
the direction of waves were made as frequently as practicable,
ually at about 10-minute intervals, by viewing at the opposite
le of the airplane.

In order to simplify the work, a wooden pelorus was mounted
the observation station with its fore and aft line parallel to the
plane's axis; the disk was turned until its indicated direction
tched the airplane's true compass heading. Each of three move-
le arms pivoted at the center of the disk was set as nearly paral-
to wave crests as could be judged. The error of setting, as indi-
ted by back sights and by comparison of results obtained on
fferent flight legs, was usually less than 10°. During flight the
server attempted to keep the arms set at all times, reading off
e settings at 1- or 2-minute intervals. These settings were noted
a recorder who also made frequent estimates of the period of
aves in each train by timing the passage of waves beneath patches
foam, floating kelp, or gulls resting on the water. The position
each observation point was determined by interpolation between
e less frequent radar position fixes.

About 50 photographs of waves were made during each flight
ith an aerial camera in order to check and illustrate typical pat-
rns. Photography, however, was found to be a poor method for
aking the primary observations because of the small area included
each picture, the uncertainty of orientation and interpretation
the pictures, and the need of observation for several minutes be-
re certain identification could be made of trains of smaller waves.

RESULTS

Maps of the wave patterns compiled after each of the four flights
igs. 1 to 4) are similar in many respects. All show the predominant
vell from the North Pacific storm area proceeding eastsoutheasterly
roughout the area, with little directional control exerted by is-
nds. Its period averaged about 10 seconds. One or two other
vells, usually having 3- to 5-second periods and moving easterly

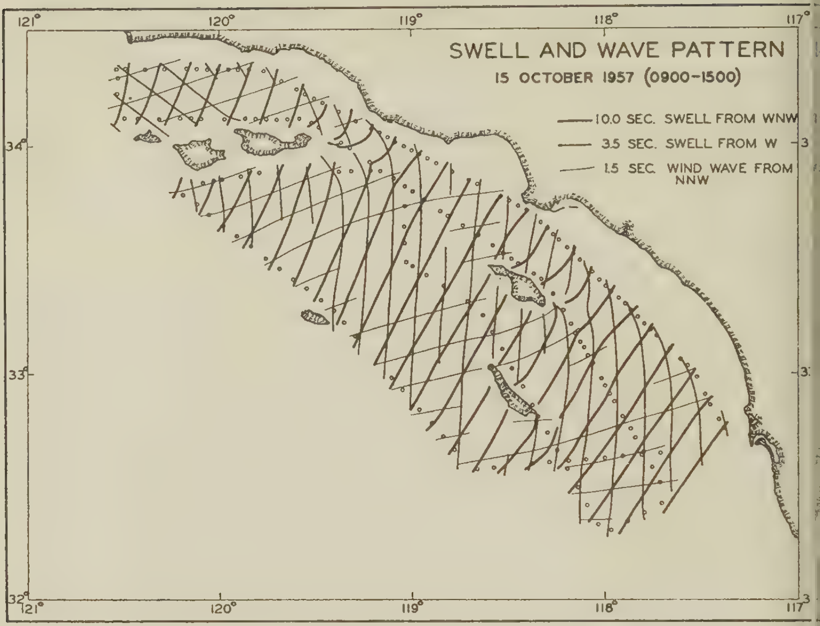

SWELL AND WAVE PATTERN
15 OCTOBER 1957 (0900-1500)
10.0 SEC. SWELL FROM WNW
3.5 SEC. SWELL FROM W
1.5 SEC. WIND WAVE FROM NNW
121°
120°
119°
118°
117°
34°
33°
32°

Figure 1. Survey of 15 October 1957. Flown aboard P5M at 1500 and 2000 feet. Cir
show positions of observation points along flight lines. The spacing of swell and wind w
lines is arbitrary and carries no implication regarding wave lengths.

or northeasterly, probably originated from storms in the cent
Pacific Ocean. A long low swell, possibly from a storm center
the southern hemisphere, was detected in the southwestern part
the area during the July survey; and it may have been present
areas of low waves in the eastern part of the area during the Ap
survey. Because of its length and lowness, it was easily obscur
by accompanying shorter and higher swells. Each survey al
showed the presence of a wind wave, usually of about 1.5-seco
period, moving southerly and following the typical wind strea
lines of the region. Long narrow parallel streaks were observed
be perpendicular to the crests of wind waves in areas of high wi
velocity near the northwestern part of the surveys. Both small
swells and wind waves are influenced by islands, mostly in the fo
of gaps in the lee of islands.

Refraction by shallow water was noted only near the shores
the mainland and islands. Cross-swells in the lee of islands we

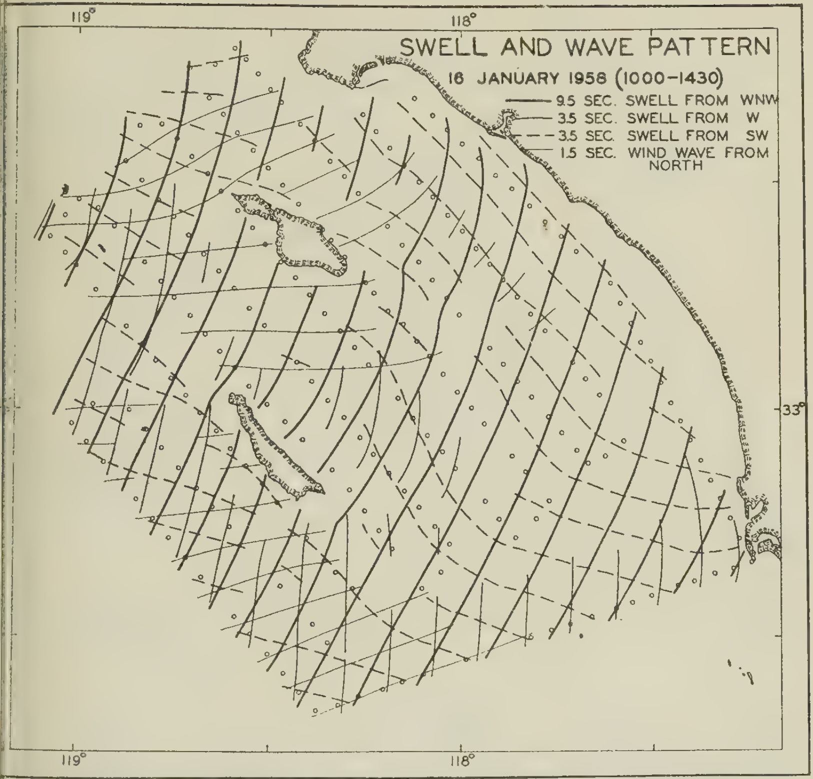

119°
118°
SWELL AND WAVE PATTERN
16 JANUARY 1958 (1000–1430)
9.5 SEC. SWELL FROM WNW
3.5 SEC. SWELL FROM W
3.5 SEC. SWELL FROM SW
1.5 SEC. WIND WAVE FROM NORTH
33°
119°
118°

Figure 2. Survey of 16 January 1958 with a closely spaced grid. Flown aboard P2V at 00 feet. Some uncertainty of the smaller swells and wind wave resulted from disturbances oduced by naval vessels operating near the middle of the survey area.

ot detectable over large areas. Reflection of waves was even less nportant. In these respects, the islands off southern California appear to have less effect on waves than do islands of the tropics. erhaps the effects of the latter islands, as observed by the Marshall landers and others, result from the relative simplicity of wave atterns in the belts of trade winds compared with the complexity patterns off southern California where they are developed by veral separate storm centers and by local winds.

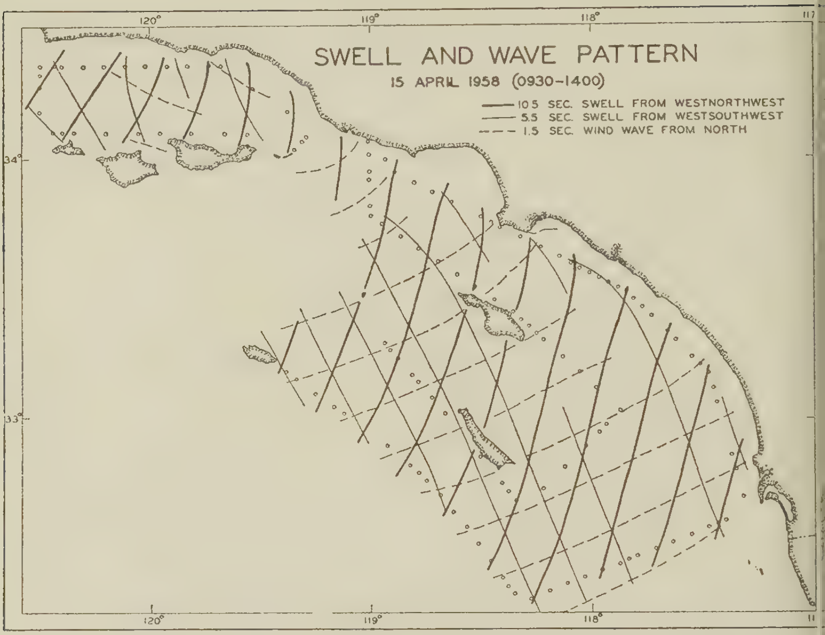
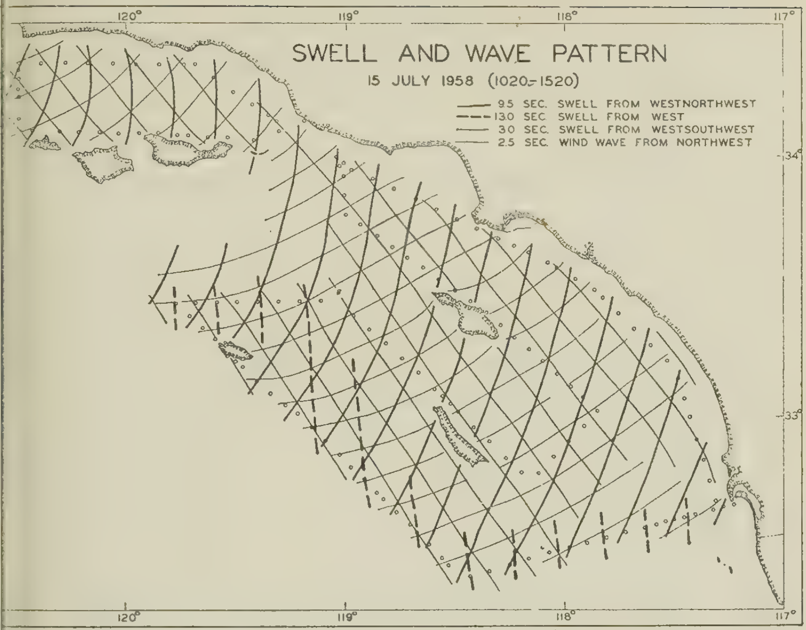

SWELL AND WAVE PATTERN
15 APRIL 1958 (0930-1400)
10.5 SEC. SWELL FROM WESTNORTHWEST
5.5 SEC. SWELL FROM WESTSOUTHWEST
1.5 SEC. WIND WAVE FROM NORTH
120°
119°
118°
34°
33°

Figure 3. Survey of 15 April 1958. Flown aboard P5M at 2000 feet.

SIGNIFICANCE

Knowledge of the pattern of wave trains off southern Californ
has several practical applications. Waves off Point Conception
the northwestern limit of the surveys are notoriously high compar
with their progressively lower height farther southeast. This is n
merely the result of the known diminution of wind velocity sout
eastward, because at least the 10-second swell is too long to ha
a local origin. Instead, the southeastward decrease in swell heig
must be due partly to protection offered by the islands which
flect much of the wave energy. The changing relationship of t
various wave trains in the region must also produce changes in t
character of wave recordings made at various places along the coa
and for different times at the same site.

Ditching tests for airplanes at sea have shown that the be
landing direction is parallel to the wave crests and troughs (Anon
mous, 1953). As a result, a 30° or 210° true course is generally co
sidered best for ditching in this region, because it is parallel to t


SWELL AND WAVE PATTERN
15 JULY 1958 (1020-1520)
9.5 SEC. SWELL FROM WESTNORTHWEST
13.0 SEC. SWELL FROM WEST
3.0 SEC. SWELL FROM WESTSOUTHWEST
2.5 SEC. WIND WAVE FROM NORTHWEST
120°
119°
118°
117°
34°
33°

ure 4. Survey of 15 July 1958. Flown aboard P5M at 400 feet because of low ceiling.

rge main swell. However, a secondary swell from the west or uthwest forms a crossing pattern that might damage an airplane nding along the main swell. If time permitted, an easier landing ght be made on the lee side of the large islands that prevent cess of some secondary swells.

The main swell from the westnorthwest is the one that contains e most energy. As it drives along the coast it is refracted so that approaches nearly directly shoreward. Since at least a small gle remains, the wave, after breaking, drives ashore in such a ection as to carry some sand southeastward. The general southstward movement of beach sand, locally contrary to the direction offshore currents, is attested by the accumulation of as much as 0,000 yd^3/year behind breakwaters and against groins of sandy aches (Johnson, 1956). During times when storm waves approach m the south or when the long swell comes from the southern misphere, the drift may be reversed locally (Shepard, 1950), but e prevalence of the main swell requires a net southeastward vement of sand along the mainland shore.

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ERTICAL DISTRIBUTION OF WIND SPEED, TEMPERATURE AND HUMIDITY ABOVE A WATER SURFACE[1]

By

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University of Washington

ABSTRACT

n observational program is described which has been used to obtain an ac-
rate determination of vertical profiles of wind speed, temperature, and vapor
essure over a salt water inlet with an over-water air fetch of about five miles.
e wind profiles show systematic anomalies of 1 or 2 %, which are not explainable
instrumental or observational error. The curvature of wind profiles over water
ows the same dependence on Richardson number as that found by others over
nd. Temperature profiles are similar in this respect, but curvature of the vapor
essure profiles shows little dependence on stability. Values of the resistance coef-
ient computed from wind profiles are at the lower limit of those reported by most
her investigators. Analogous coefficients computed from temperature and vapor
essure profiles have the same magnitude as the resistance coefficient but show
greater dependence on stability.

INTRODUCTION

One would like to specify the energy and mass transfer at the arth's surface in terms of as simple a set of atmospheric parameters s possible. At its simplest, this set might be wind speed, temperature nd humidity at the surface and at a single height above; more ealistically it might be vertical distributions of wind speed, temperture and humidity in the air near the surface. However, if one ttempts to achieve the latter for the great ocean areas, he finds hat there are few data available from which transfer calculations an be made; and worse, observations vary to such an extent that, r example, the roughness lengths reported from various studies nder apparently similar conditions differ by several orders of agnitude. This represents an unexplained difference in drag coefcient of an order of magnitude which is obviously intolerable if one wants to understand wind stress on the water. These consideratio illustrate the need for reliable observations over the oceans.

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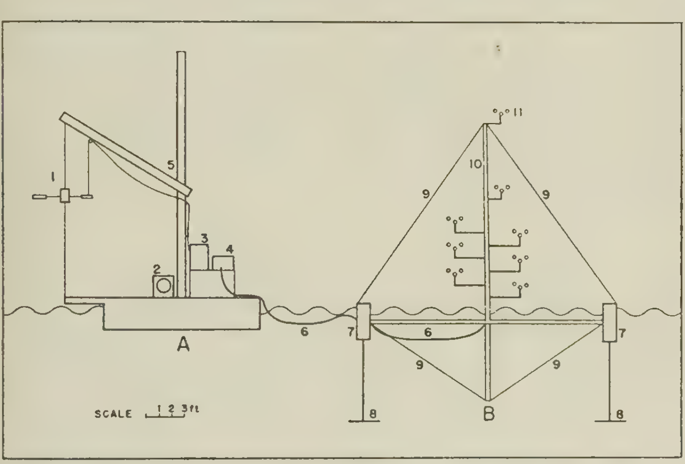
An observational program conducted during the past few sur mers at the Friday Harbor Laboratories of the University of Was ington has been designed to meet part of this need.

FIELD EQUIPMENT AND METHOD OF OBSERVATION

Wind speeds at eight levels, from 31 to 442 cm above the wat surface, were measured with sensitive rotating cup anemomete manufactured by Casella after Sheppard's design. These were su ported above the water by an anchored skeleton raft 20 feet squar with buoyant tanks located at its four corners. These tanks bare supported the weight and therefore responded only slowly to passi waves (see Fig. 1). A horizontal plywood disk was mounted eig feet below each of the four tanks to further reduce rocking due waves. In all waves encountered, vertical motion or rocking of th raft was unnoticeable.

The anemometers were supported from a central mast ($^3/_4$ inc galvanized iron pipe) from which individual supports extended tw feet horizontally outward. As shown in Fig. 1, the lower six we arranged alternately on either side of the mast and were pointe slightly upwind to eliminate interference between adjacent an mometers and between mast and anemometers. The top two instr ments had enough vertical spacing so that their supports could pointed directly into the wind. Seven of these anemometers, of t electrical contact type, were connected by underwater cable counters on an anchored log raft shown at the left of Fig. 1; o anemometer with dial was read with the aid of field glasses fro that raft. The anemometers were carefully compared in a variet of wind conditions prior to observation and corrected calibratio curves were constructed. The authors are confident that the hour response of each anemometer was known to within about 2 cm/s of the response of the anemometer that was used as standard. Fo of the anemometers were compared at low wind speeds after t observations were completed and no change in calibration was note

Dry and wet-bulb temperatures were determined at 40, 80, 1 and 320 cm above the surface by a micropsychrometer made of tw 40 gauge copper-constantan thermocouples. This instrument w mounted on a vertical wire track which ran upward from the wat face three feet outboard from the raft shown at the far left of . 1. The micropsychrometer was raised and lowered manually ough the desired vertical range and was ventilated by natural d. A thermos bottle of sea water, collected at the surface at 15 ute intervals, served as the reference temperature; the thermo-uple output was read visually from a Leeds and Northrup Model 35 B D.C. amplifier. A series of readings was made each minute; ese consisted of two readings of temperature and one of wet-lb temperature at each level. Thus average time between readings s five seconds, an interval which was considered to be sufficiently ng to absorb the lags of thermocouples and amplifier and to allow observer to make accurate readings representative of about one ond.



igure 1. Sketch showing recording raft (A) and anemometer raft (B) viewed from up-d. Shown are: Thermocouple psychrometer (1), generator (2), D.C. amplifier and ther-ouple outputs (3), wind register (4), mast and yard-arm (5), underwater cable (6), floats wave dampers (8), guy wires (9), anemometer mast (10), anemometer (11).

Made at the same time but not reported in this paper were ob-vations of solar and infra-red radiation, of evaporation from a ating pan, and of diffusion of particulate matter; the latter ob-vations were made by a group from the Hanford Laboratories The General Electric Company.

Observations were made during a four-day period in July 1958 the center of East Sound, a salt water inlet about one mile wide,

seven miles long, and 90 feet deep. East Sound opens to the sou
and is surrounded on the other three sides by Orcas Island, locat
in the San Juan Archipelago between Vancouver Island and t
mainland at about Lat. 49° N. The shores on both sides of Ea
Sound rise rather abruptly to a height of several hundred feet, b
the terrain at the closed north end is low and flat. During the peri
of observation the wind direction at the raft was parallel to t
shore line and directed from the open water at the mouth. Althou
trajectories of air reaching the raft appeared to be over water
the way from the mouth five miles distant, there may have be
times when air from the shore only a mile from the raft was mix
into that approaching from the mouth.

RESULTS

Average values of wind speed, temperature and vapor pressu
for 30 one-hour periods are tabulated in the Appendix. Some re
resentative profiles are shown in Fig. 2, in which circled numbe
specify the hourly periods of the individual profiles. A few of t
wind profiles are also shown by the subjectively drawn dash
curves. These emphasize the systematic anomalies which are 1
$2\,^0/_0$ of the wind speed. No such anomalies are evident in t
temperature and vapor pressure profiles. Individual measuremen
of these profiles relative to the reference values are considered
have maximum errors, due to sampling, of .02° C and .04 m
respectively. There probably is a greater uncertainty in the s
surface temperature than in the above because it was sampled on
four times during each hour; also there is a corresponding ambigui
in the wind speed relative to the sea surface because surface dri
has been neglected.

Details of Wind Profiles. Many investigators have found th
wind profiles are smooth curves when based on measurements ma
over uniform land surfaces. Under conditions of neutral hydrostat
stability, the curves become straight lines if the wind speed
plotted against the logarithm of the height, z. In stable air su
plotted curves are slightly convex towards the log z axis, and
unstable air the curvature is reversed (Deacon, 1949). While t
velocity profiles shown in Fig. 2 are in general agreement wi
the above, the readings from anemometers at 60, 133, and 213 c
which are those shown on the left of the mast in Fig. 1, are wi

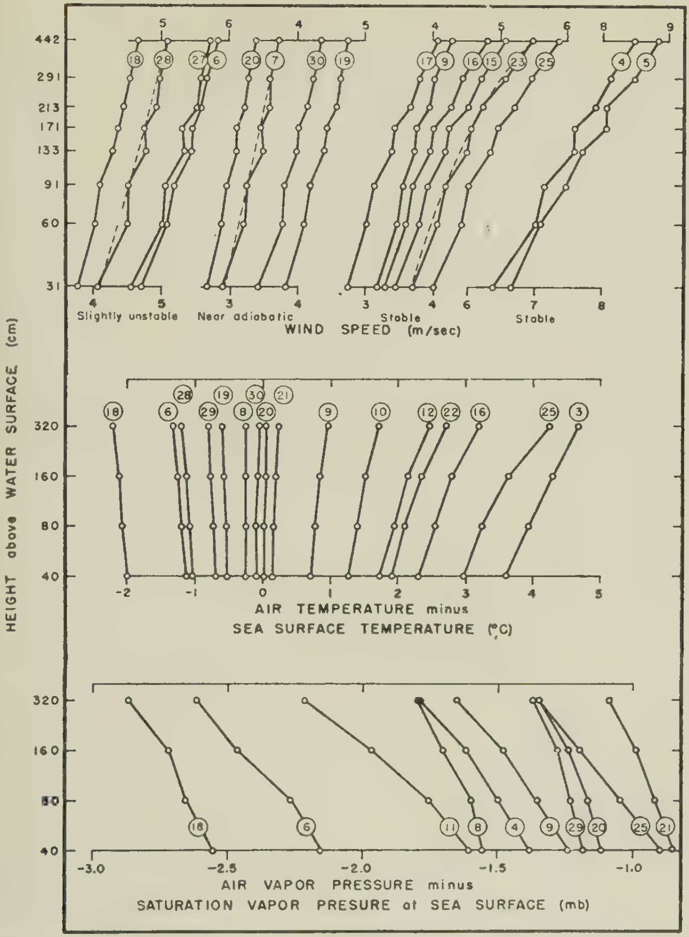


Figure 2. Representative profiles of wind, temperature, and vapor pressure.

wo exceptions higher than would be predicted from smooth curves rawn for the other levels. This throws suspicion on the calibration nd installation of the instruments; in particular, since the aneometers giving anomalously high readings were on the opposite de of the mast from the others, it seems possible that the rotation f the anemometer cups was influenced by the presence of the mast r of the other anemometers. In recognition of these possibilities he following considerations are pertinent:

1) The anemometers were calibrated to a relative accuracy of 1
   2 cm/sec before the observations, and the calibration was r
   checked afterwards for the four anemometers which had bee
   mounted from 91 to 213 cm.
2) Special mountings were used to assure vertical orientation of th
   anemometers.
3) Similar anomalies (unpublished) have been observed in at lea
   five different over-water locations in the same general area ov
   a period of several years. Profiles free of anomalies have bee
   observed only rarely and always at low wind speeds.
4) During observations at East Sound in 1957, the anemomet
   array differed from that described herein principally in the fa
   that, height for height, the anemometers were on opposite sid
   of the mast with respect to the wind direction. Nevertheless th
   vertical positions, algebraic signs, and magnitudes of the anom
   alies were consistent with those reported here.
5) Although anemometers were not often interchanged because o
   the practical difficulties involved, when this procedure was trie
   in 1957 it did not change the profile anomalies.
6) A mock-up of the mast and anemometer was tested in a win
   tunnel to see if interference between one anemometer and an
   other or between mast and anemometer could explain the ano
   malies. The mock-up was not an exact duplicate of the mas
   used in the observations but it differed only in ways which woul
   be expected to increase any interference: the arms supportin
   the anemometers were six inches shorter than those shown i
   Fig. 1, and two anemometers were mounted at the same leve
   on opposite sides of the mast rather than at different levels, a
   in practice. The mast size and anemometers were identical t
   those used in the field. It was found that the wake behind a
   obstacle, whether anemometer or mast, affected the reading c
   a second anemometer only if the latter were within 30° of bein
   directly downstream of the obstacle. This extreme was never th
   case in practice.

In view of the above it is difficult to accept an explanation based o
a presumption of persistent errors in calibration or mounting of th
instruments, but further investigation of this point is called fo

A final bit of evidence suggests that what has been observed her
is an effect of waves at the surface. Throughout periods 1 throug

the second, fourth, and sixth anemometers from the bottom icated relatively high velocities compared to the first, third, fifth. Wind profile 5 shows that these features reversed between fourth and fifth period and that during the fifth period the sea hed its roughest state, as indicated by the fact that the elec- al generator was swamped during this period, thus interrupting perature and vapour pressure observations. Subsequently, the d speed decreased, the sea became less rough, and the anomalies urned to their original positions.

f the anomalies are presumed to be 'real', it is still uncertain as hether they are anomalies in the true mean wind velocity pro- or in the eddy size distribution. An explanation based on the er hypothesis would infer the existence of ordered vortices in form of long cylindrical rolls with axes horizontal and normal the mean wind. If these moved past the anemometers (perhaps h the speed of the larger surface waves) and if they had a persis- t size and vertical distribution, they would then contribute ferently to the variability of the three-dimensional wind at cer- n heights than at others. In view of the complicated way in ich cup anemometers respond to changes in wind speed and gle of attack (Middleton and Spilhaus, 1953), it might be expected at these ordered vortices prejudice anemometers to read higher at tain heights than they would in the absence of such vortices.

The above possibility might be checked by simultaneous measure- nt of wind profiles, using anemometers of a basically different sign. Takahashi (1958), using thermocouple anemometers mounted five heights from a small boat, found an apparent discontinuity slope of his measured wind speed versus log z curves. This he plained as representing a transition from a 'hydrodynamically ugh' profile which had been established over land to a 'hydro- namically smooth' profile becoming established over the water. is explanation is inadequate to account for the several kinks in more detailed wind profiles of Fig. 2.

Effect of Thermal Stratification. The outstanding feature of the nd and temperature profiles shown in Fig. 2 is their logarithmic m in near-adiabatic conditions and a stability effect as previously ntioned. However this effect appears to be less consistent among vapor pressure profiles.

The influence of stability upon wind profile has been expressed by Lettau (1949), Panofsky (1952), Monin and Obukhov (195 Businger (1955), Sheppard (1958), and others by the 'log plus linea equation as a first approximation. This equation arises if it is as sumed that

$$K_m = k\sqrt{\tau/\varrho}\, z/(1-mz), \qquad ($$

where K_m is the eddy viscosity defined by

$$\tau/\varrho = K_m \frac{\partial u}{\partial z}. \qquad ($$

Here u is the mean wind speed at height z; k, the Karman numbe τ, the stress at the surface; ϱ, the density of the air; and m, a par meter existing in the presence of a turbulent vertical flux of enthal (heat). Upon substitution of (1) into (2) and on integration fro surface to height z, the log plus linear equation is obtained:

$$u = (1/k)\sqrt{\tau/\varrho}\left(ln\frac{z+z_0}{z_0} - mz\right). \qquad ($$

The common assumption has been made that the roughness lengt z_0, appears in the numerator of the logarithmic term in order th u vanish at $z = 0$. Eq. (3) shows that the linear term produces curvature to the logarithmic profile which has the expected sen when the sign of m is the same as the sign of the upward heat flu

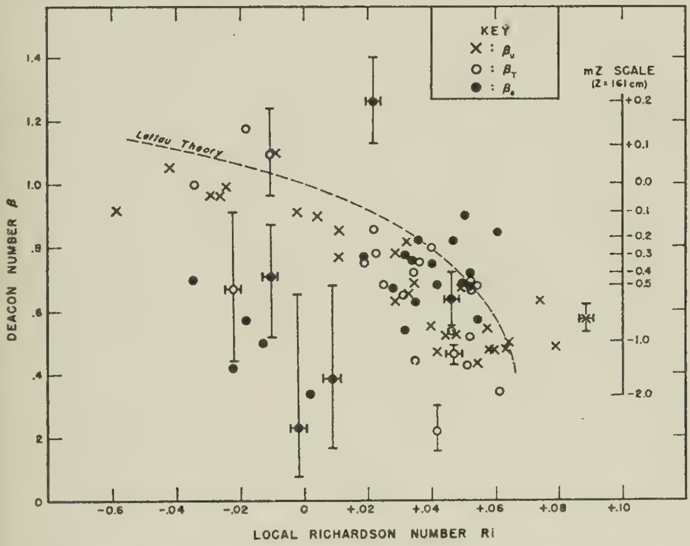
A dimensionless parameter which has frequently been used describe the relative profile curvature is the Deacon number, defined by

$$\beta_q = -z\frac{\partial^2 q}{\partial z^2}\bigg/\frac{\partial q}{\partial z}, \qquad ($$

where q may represent wind speed, temperature, or the density water vapor or other matter. From (1), (2), and (4), using $q = u$, follows that $mz = (\beta_u - 1)/\beta_u$, so that (3) may be written

$$u = (1/k)\sqrt{\tau/\varrho}\left(ln\frac{z+z_0}{z_0} + \frac{1-\beta_u}{\beta_u}\right). \qquad ($$

The Deacon number for wind, β_u, has been computed from (using winds at 31, 91, 171 and 442 cm. These levels were chosen o avoid levels at which the observed wind speed appeared to be ematically high for the reasons given previously. Values of β_u ch then apply to a height of 161 cm are shown in Fig. 3 (crosses) tted against the Richardson number, *Ri*, computed for the same ht[2]. The *mz* scale for this height is given on the right-hand side



igure 3. A plot *vs* local Richardson number, *Ri*, of Deacon's number, β (a measure of relative profile curvature) for wind, temperature, and vapor pressure.

Fig. 3. Assuming a standard deviation in relative wind speed asurements of ± 1 cm/sec, the standard error of β_u is approximately 04; for a standard deviation of temperature of $\pm .01°$ C, the standd deviation of *Ri* becomes about $\pm .002$. The scatter of the β_u ues appears to be somewhat larger than is to be expected from

---

The Richardson number, usually thought of as a nondimensional measure of stability of the atmosphere, is defined as:

$$Ri = g\left(\frac{\partial T}{\partial z} + \Gamma\right) \Big/ T\left(\frac{\partial u}{\partial z}\right)^2$$

re g is the acceleration of gravity, T, the Kelvin temperature, and Γ, the adiaic lapse rate. In our computations Γ has been neglected because it is small comed to $\partial T/\partial z$ near the surface.

instrumental error alone, although plots of β_u against other stabil parameters resulted in still greater scatter.

It has been shown by Lettau (1956) that β_u appears to be a uniq function of *Ri* for over-land profiles, provided $Ri < .06$. His relati between β_u and *Ri* is shown by the curve in Fig. 3, which agr fairly well with these over-water observations centered at 161 c An attempt was made to determine the uniqueness of this relati by computing β_u for two heights within each profile. When th values were plotted against the Richardson number for the a propriate height (the local Richardson number), those obtain from the upper portion of the wind profiles were significantly larg than those for the lower portion in nearly all cases. It seemed p sible that, even though the levels at which the wind speed w systematically high were excluded from these computations, t influence of the kinks had not been entirely removed. Therefore t procedure was repeated for subjectively drawn wind profiles, b the same tendency was noted. In the same manner, the constan of *m* from eq. (3) for both portions of the profiles was investigat by plotting it against the Richardson number at a fixed heig Again values from the upper portion were significantly more positi Although the dependence of β_u on *Ri* is roughly consistent w Lettau's equation, this dependence appears not to be independe of height. This implies that the wind profiles are not accurat and completely expressible by a log plus linear equation. Th negative conclusions are tentative, however, due to the uncertain arising from the profile kinks.

The effect of stratification upon curvatures of temperature a moisture profiles may be investigated with the aid of the Deac numbers for temperature and vapor pressure, β_T and β_e, respective These, computed from measurements at 40, 80, 160 and 320 c assuming log plus linear profiles, apply to a height of 112 cm. is shown in Fig. 3 by open circles, β_e by solid circles. The line se ments indicate some estimates of the standard deviations of β_T a β_e arising from assumed standard deviations of ±.01° C and ±.015 m respectively. Values occuring for $|T_{40}-T_{80}| < .04°$ C or $|e_{40}-e$ $< .04$ mb are not plotted due to the excessively large errors to expected under these conditions; here *e* refers to vapor press and the subscripts to the heights of measurement. The data do n indicate any significant difference between β_u and β_T, whereas is unexpectedly small during lapse and near-adiabatic conditio shown by Lettau (1957) that the eddy diffusivities for momentum, t and moisture must increase with height at different rates if respective Deacon numbers differ. Therefore our over-water data gest that the ratio of the eddy diffusivity for heat to that for nentum was roughly constant with height, whereas the ratio of eddy diffusivity for vapor to that for momentum changed with ght above the surface.

he near-isothermal temperature profiles, omitted in the above ussion, were accompanied by sea surface temperatures roughly C warmer than the air. Similar apparent discrepancies, reported Roll (1948) and by Deacon, *et al.* (1956), are noticeable in data ished elsewhere. Roll's suggested explanation of evaporative ing from the surface is incredible, because it implies a laminar er layer of some centimeters in depth. Deacon bases his explan- n on Priestley's (1955) discussion of heat flux near the ground. latter believes that above some level, near to but not coincident h the surface, an upward flux of heat can be maintained in an hermal atmosphere; the mechanism responsible is supposedly convection. Below that level the flux is maintained by "forced vection", that is, by mechanically driven eddies, and in this llow layer a decrease of temperature with height must prevail. r observations indicate that if such conditions did occur over the , the layer of forced convection lay below 40 cm.

Relative Profile Gradients. It is desirable to express the vertical dient of a micrometeorological quantity in terms of a measure- nt at the surface and at a single height above. This requires roduction of a parameter which describes the relative profile dient, such as the profile contour number (Lettau, 1957: 339) ined by

$$\alpha_q = z \frac{\partial q}{\partial z} \Big/ (q - q_0). \tag{6}$$

ain q is the property of the particular profile under consideration d q_0 its value at the surface. If α is regarded as a constant for articular height above a water surface, the stress τ, for example, then be written in terms of a single wind speed with the aid (3) and (6), using $q = u$:

$$\sqrt{\tau/\varrho} = \frac{k\alpha_u}{1 - mz} u. \tag{7}$$

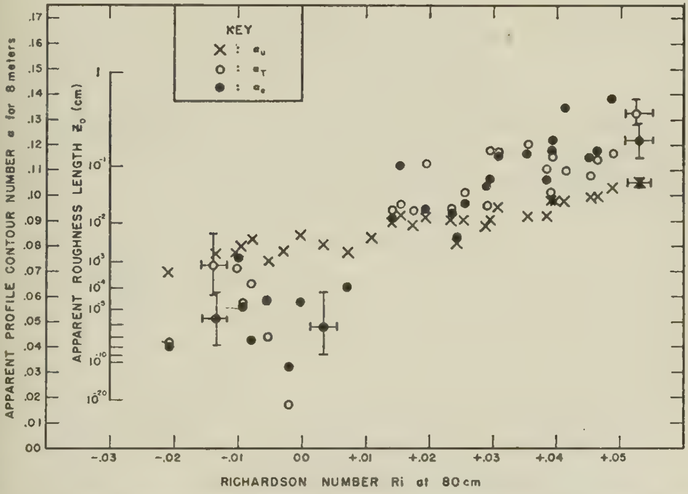
There have been numerous measurements of $k\alpha_u$ over water b
variety of methods. The most common of these, at low or moder
wind speeds, has been through use of (7), taking $k = 0.4$ but
suming $m = 0$ and using winds at two heights. In this case t
product $k\alpha_u$, called the resistance coefficient, γ, by Sverdrup (195
is obtained from

$$k/\gamma = 1/\alpha_u = ln\, z/z_0 = ln\, z/z_2 + \frac{u_2}{u_1}\, ln\, z_2/z_1 \Big/ \left(\frac{u_2}{u_1} - 1\right)$$

which follows from (3) and (7). From (8) it is evident that the
sistance coefficient and contour number depend upon the refere
height, z. It is also implicit in (8), but not so evident, that z_0 v
have an apparent dependence upon stability due to the assumpti
of a logarithmic profile which may not actually exist. Therefore t
resistance coefficient and profile contour numbers should be term
"apparent" when computed from (8), since they will also show
apparent variation with stability. Furthermore, it follows from
that the magnitude of this apparent variation will depend up
the heights of measurement, z_1, and z_2, under nonadiabatic co
ditions. Nevertheless it is of interest to present values of appare
contour number because they are directly comparable under ad
batic conditions to those found by other investigators if the sa
reference height is used. A height of 8 m will be used here in a
cordance with Sverdrup. In order to minimize the influence of t
kinks in the wind profile, α_u was computed from winds at the fo
lowest levels by the method of least squares, assuming a logarith
increase of wind speed with height. The values are shown in Fig
(crosses) plotted against Richardson number at 80 cm. In the ran
of wind speeds encountered (3 to 9 m/sec) there did not appear
be any direct dependence of α_u on wind speed, that is, no dependen
other than that introduced by the fact that wind speed and Ric
ardson number are correlated. For convenience, a roughn
length scale for z_0 is included on the left-hand side of Fig. 4. T
adiabatic value for α_u is about 0.082, which is significantly smal
than the value 0.14 corresponding to the oft-quoted roughn
length of 0.6 cm for the ocean (Sverdrup) and which is smal
than most of the values reported by Wagner (1958) for the G
of Mexico.

[3] Other writers have referred to γ^2 or $2\gamma^2$ as the resistance or friction coeffici

ver water the profile contour numbers (eq. 6) for temperature
water vapor can also be measured if it is assumed that the
perature and vapor density of the air at the surface are the
ilibrium values for sea water at the measured temperature. (The
arent profile contour number for water vapor, α_e, is frequently



gure 4. A plot *vs* Richardson number, *Ri*, computed for 80 cm, of profile contour num-
α (a measure of the relative profile gradient) for wind, temperature, and vapor density.

erred to as the Montgomery evaporation coefficient.) Values of
and α_e were computed from (8) using $T - T_0$ and $\varrho_w - (\varrho_w)_0$ in
ce of u, where ϱ_w is the water vapor density of the air and $(\varrho_w)_0$
saturation vapor density corrected for a salinity of 29 $^0/_{00}$. A
ght of 8 m was used for the reference level, and 40 and 160 cm
the levels of measurement. The profile contour numbers for
nperature and water vapor are shown in Fig. 4 by open and solid
cles, respectively. Four values of α_T have been omitted for periods
en the air and sea surface temperatures were nearly equal. Within
its of observational error, α_T and α_e appear to be identical but
w greater dependence upon *Ri* than does α_u. No significant
ondary dependence of α_T or α_e upon wind speed was evident;
s is in disagreement with Brocks (1955) who found such a de-
ndence when he analyzed data gathered over the oceans by Wüst,
ntgomery, and Sverdrup. Also, when his value of α_e for adiabatic

temperature stratification and moderate wind speeds is adjusted the same basis as those reported here, it is found to be 0.11, alm double the value of 0.06 which we found for similar conditio On the other hand, our values of both α_u and α_e do agree clos with those which can be deduced from the data of Takahashi (19 for Kagoshima Bay in southern Japan.

ACKNOWLEDGMENTS

The field observations, which were made as part of a meteorolo course, could not have been obtained without the aid of stude Bruce Lieske and Norman Thyer. Mikio Miyake did most of wind-tunnel work of testing anemometer exposures.

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APPENDIX A

Hourly Period Number	*Date 1958*	*Local Time at Start of Period*	*WIND SPEED (cm/sec) at Listed Heights (cm*						
			31	*60*	*91*	*133*	*171*	*213*	*291*
1	7/7	1530	613	672	685	728	733	764	789
2	7/7	1645	611	673	684	732	733	768	790
3*	7/7	1805	692	765	782	832	834	867	895
4†	7/7	1916	639	701	714	759	760	790	813
5	7/7	2142	665	706	746	772	807	807	848
6	7/8	0537	468	506	516	543	547	558	567
7	7/8	0705	424	464	468	498	494	513	518
8	7/8	0820	289	319	323	342	340	356	358
9	7/8	0933	317	345	354	373	375	393	402
10	7/8	1046	351	382	392	417	420	441	456
11	7/8	1202	338	369	378	403	406	429	444
12	7/8	1312	378	415	426	456	459	485	501
13	7/8	1426	374	408	420	448	452	475	493
14	7/8	1541	342	374	386	413	419	445	464
15	7/8	1647	345	378	391	419	424	450	470
16	7/8	1755	326	358	369	396	401	425	443
17	7/8	1910	273	301	313	339	343	365	379
18	7/9	0721	375	400	408	427	434	442	452
19	7/9	0830	382	408	417	438	444	456	464
20	7/9	0945	266	286	294	308	310	320	327
21	7/9	1059	206	225	228	240	241	251	258
22	7/9	1507	370	402	413	441	445	466	483
23	7/9	1615	368	405	418	450	457	471	506
24	7/9	1733	345	388	397	430	439	467	493
25	7/9	1837	400	442	452	485	495	519	547
26	7/9	1947	413	449	460	489	499	518	543
27	7/10	0603	454	500	503	533	529	551	557
28	7/10	0710	404	446	449	475	472	491	496
29	7/10	0838	336	366	372	390	389	400	409
30	7/10	0945	340	375	378	398	401	413	422

* Anemometer reading at 442 cm is for first half of period only, due to faulty cour operation last half.

† Anemometer reading at 442 cm is for last half of period only, due to faulty cour operation first half.

APPENDIX B

iod ber	*Temperature (° C) at Listed Height (cm)* sfc.	40	80	160	320	*Vapor Pressure (millibars) at Listed Height (cm)* sfc.	40	80	160	320
*	16.80	19.66	19.91	20.18	20.53	—	—	—	—	—
	16.00	19.68	20.04	20.36	20.83	17.91	16.13	15.91	15.81	15.49
	15.76	19.34	19.68	20.02	20.42	17.60	16.52	16.38	16.26	16.18
	15.21	17.70	17.88	18.15	18.41	17.01	15.63	15.51	15.39	15.22
†	13.98	—	—	—	—	15.72	—	—	—	—
	14.61	13.48	13.40	13.34	13.27	16.37	14.21	14.10	13.90	13.75
	14.49	13.67	13.67	13.64	13.61	16.24	14.61	14.58	14.53	14.44
	14.19	13.92	13.92	13.92	13.93	15.93	14.37	14.33	14.22	14.13
	14.06	14.74	14.81	14.90	15.01	15.79	14.50	14.37	14.26	14.08
	14.26	15.51	15.63	15.76	15.96	16.01	14.60	14.48	14.32	14.09
	14.50	15.65	15.76	15.93	16.17	16.25	14.64	14.48	14.28	14.03
	14.26	15.97	16.19	16.39	16.71	16.01	14.69	14.51	14.36	14.13
	14.50	16.17	16.38	16.61	16.89	16.25	14.92	14.76	14.59	14.36
	14.76	16.62	16.84	17.07	17.50	16.53	15.20	15.02	14.84	14.54
	14.72	17.09	17.37	17.66	18.10	16.48	15.06	14.88	14.68	14.41
	14.56	16.84	17.09	17.34	17.75	16.31	14.92	14.77	14.58	14.34
	14.73	16.40	16.62	16.92	17.34	16.49	15.35	15.22	15.05	14.84
	15.28	13.27	13.19	13.14	13.06	17.09	14.53	14.43	14.37	14.22
	14.04	13.50	13.49	13.46	13.42	15.77	14.58	14.53	14.46	14.36
	14.16	14.16	14.17	14.19	14.20	15.90	14.78	14.73	14.66	14.54
	14.46	14.58	14.61	14.65	14.68	16.22	15.36	15.30	15.23	15.13
	15.10	17.00	17.18	17.44	17.80	16.89	15.69	15.56	15.43	15.23
	15.21	18.18	18.44	18.78	19.34	17.01	15.68	15.51	15.33	15.12
	15.10	18.29	18.60	19.07	19.87	16.89	15.78	15.58	15.40	15.16
	14.97	17.92	18.19	18.59	19.20	16.76	15.86	15.71	15.56	15.40
	14.63	16.53	16.68	16.91	17.35	16.39	15.46	15.36	15.26	15.11
	14.24	13.15	13.13	13.04	12.96	15.98	14.70	14.69	14.61	14.55
	14.09	13.05	13.00	12.95	12.87	15.81	14.57	14.52	14.45	14.34
	14.13	13.43	13.39	13.34	13.31	15.86	14.68	14.63	14.58	14.49
	14.46	14.35	14.35	14.38	14.40	16.22	15.15	15.16	15.07	14.97

Vapor pressures are missing due to wet-thermocouple becoming partially dry.

Vapor pressures represent only a 39 minute average, due to wet-thermocouple being tially dry part of period.

† Measurements are missing because electrical generator was swamped by a large wave.

NOTES CONCERNING THE HALOCLINE IN THE NORTHEASTE PACIFIC OCEAN[1]

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ABSTRACT

The quasi-isothermal halocline between depths of about 100 and 200 m i striking feature of the temperature-salinity characteristics in the northeast Pacific, north of about 40° N. An hypothesis is offered to explain the origin of t feature in terms of circulation, dilution, and winter mixing.

INTRODUCTION

Over extensive areas in the northeastern Pacific Ocean, north about 40° N, the vertical distributions of temperature and salin are characterized by a quasi-isothermal halocline. Although t halocline is limited to depths of less than 250 m and although tem eratures and salinity ranges are variable in different parts of t region, the halocline is a striking feature of the temperature-salin diagrams. Investigations by Professor T. G. Thompson and students (Goodman and Thompson, 1940) were among the first demonstrate the major features of the water masses in the nort eastern Pacific. The most recent summary of the thermohali relationships and of the geographic range of the halocline is Dodimead (1958).

It is the purpose of this paper to present an hypothesis concerni the processes that contribute to the formation of the halocline parts of the northeastern Pacific. Although the discussion is limit to this particular feature and area, it is believed that the princip are of broad application to an analysis and understanding of t processes that affect the distribution of properties in shallow depths of the oceans.

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[1] Contribution No. *226* from the Department of Oceanography of the Univers of Washington. Publication was supported in part by the Agnes H. Anderson F of the University of Washington.

OBSERVED CONDITIONS

Characteristic vertical distributions of temperature and salinity ring the summer months in the northeastern Pacific (approxitely 45° N) are shown in Fig. 1. In the surface layer, usually tween 75 and 100 m thick, there is a small increase in salinity d a relatively large decrease in temperature; however, in the ocline below it, usually between 75 and 150 m thick in the whole a, the temperature is relatively constant while the salinity inases rapidly with depth, this salinity increase usually being ater than 1 ‰. Despite temperature and salinity variations from ce to place, it is characteristic of the region that the salinity at base of the halocline is always nearly 33.8 ‰. This feature has en discussed by Tully (1953), by Tully and Dodimead (1957), d by Dodimead (1958). These authors recognized the importance the halocline and have described methods for estimating the linity at its base (their *index salinity*); furthermore, by assuming at the upper zone (see Fig. 1) results from dilution of water of

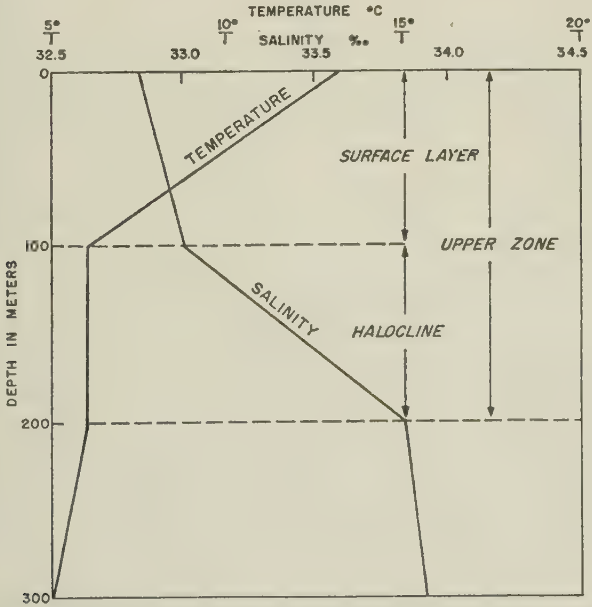


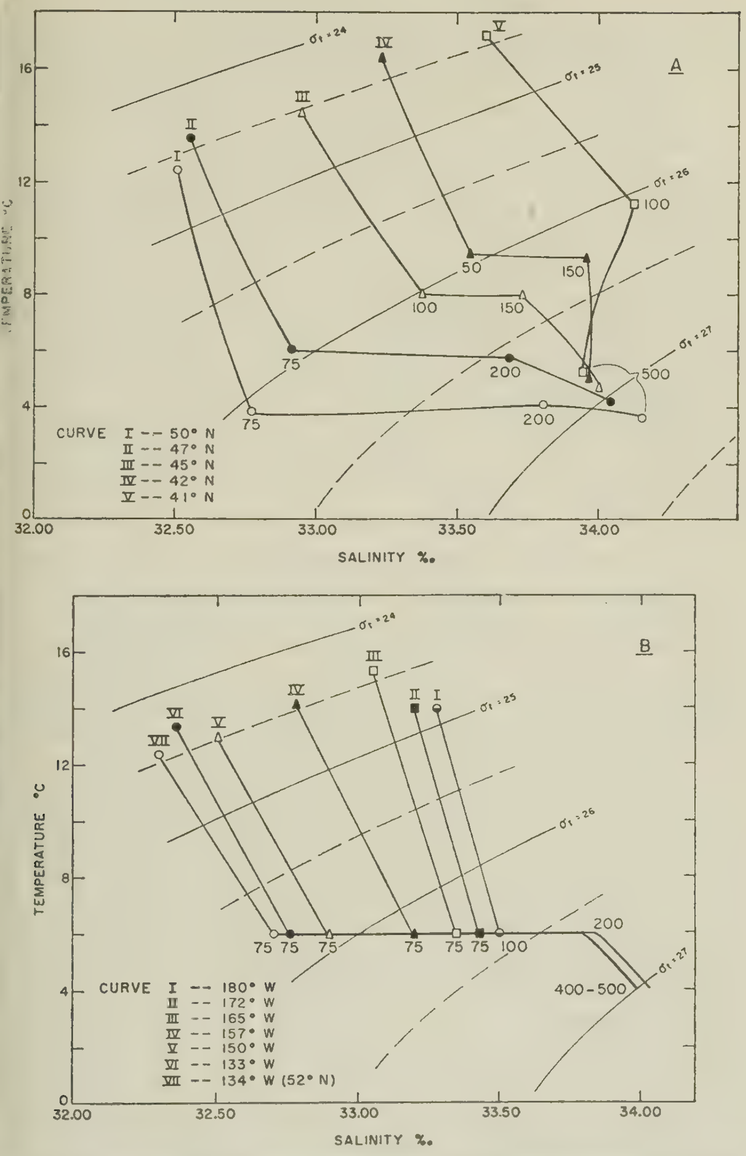
Figure 1. Schematic distributions of temperature and salinity at about 45° N, and termlogy applied to features in the upper zone. All values approximate.

about 33.8 $^0/_{00}$ salinity, they have computed the accumulation fresh water. This "depth of fresh water in the upper zone" has bee used by Tully and Dodimead to draw certain conclusions concernin the speed of surface circulation in the northeastern Pacific. Becaus the halocline is a layer of high stability (rapid increase of densit with depth), it seems reasonable to assume that conditions alterin the density in the surface layer and in the upper part of the halocline will not affect waters below this. Observations in the are during the stormy winter months (Dodimead, 1958) support th conclusion, for they show not only a well-mixed surface layer wit uniform temperatures close to those in the halocline but condition in the deeper parts of the halocline similar to those found durin the summer.

Examination of available T-S diagrams for an area extending fro 180° W to the North American continent and from 40° N to th coast of Alaska and the Aleutian Islands showed that the haloclin is present over almost the entire area. The following generalization may be made about the regional characteristics of the upper zone

1. The salinity at the base of the halocline is about 33.8 $^0/_{00}$ bu tends to be greater than this near the American coast.
2. The average salinity in the surface layer (above the halocline is greatest in the south, where the water characteristics approac those of the Central Water mass, and decreases northward an eastward.
3. Temperatures in the halocline, approximately 10° C in the sout (about 40° N), decrease in midocean with increasing latitude being slightly less than 4° C at about 50° N and over a wid area south of the Aleutians and the Gulf of Alaska. North about 45° N, on approaching land, the halocline temperature become warmer than in midocean. South of 45° N the halocline temperatures are cooler than those offshore.
4. Temperatures in the halocline are more nearly uniform midocean than in coastal waters. To the north, temperature at the base of the surface layer or in the upper part of th halocline are commonly about 1° C lower than those in th deeper part of the halocline. In the southeast, the upper portions of the halocline are warmer than the deeper portions.

Some of the major features of the geographic variations of th halocline are shown in the schematic T-S curves in Figs. 2A and 2



igure 2. *A*. Generalized T-S relationships at about 155° W extending from 50° N (Curve I) 1° N (Curve V). Depths in meters are indicated. *B*. Generalized T-S relationships ex- ling from 180° to 133° W along approximately 45° to 47° N, except Curve VII which 1 52° N. Depths in meters are indicated.

Fig. 2A, based on observations made during summer months about 155° W, represents the relationships at various latitudes e tending from 41° to 50° N. These curves are representative of chang in the upper zone with latitude in midocean. Fig. 2B illustrates t way in which the characteristics change from west to east. The curves are based on summer observations at stations where hal cline temperatures are about 6° C. Moving eastward from 180° the most notable feature is the progressive decrease in salinities the upper part of the halocline and in the surface layer. The fa that salinities in the surface layer increase with depth indicat that dilution must occur during the summer as well as during t winter. These idealized curves are not representative of the mo fied T-S relationships near land. Curve I in Fig. 2A shows t temperature inversion in the upper part of the halocline that typical of conditions over a large area in the higher latitudes. The deviations will be discussed later.

THE PROBLEM

The halocline is a conspicuous and permanent feature in the nort eastern Pacific and, allowing for annual changes in the surface lay is present throughout the year. The fact that both temperature a salinity characteristics in midocean vary with latitude but are rel tively uniform for long distances from west to east suggests th the structure is in some way associated with the prevailing curre systems. Most of the region under consideration lies between t Sub-Arctic Water mass and the Central Water masses (Sverdru *et al.*, 1942). It is tempting, therefore, to postulate that the varia T-S relationships in this region can be explained in terms of late mixing on surfaces of equal density. However, it is most unlike that such processes would produce a layer of uniform temperatu and varying salinity. Tully and Dodimead recognized that the regi is one of net dilution (*i. e.*, where precipitation exceeds evaporatio and from calculations of the "thickness of the fresh water laye and from the annual excess of precipitation, they estimated t "age" of the water in the upper zone. However, they did not off any explanation of the processes that lead to the development the halocline with uniform temperatures. Therefore, the proble at hand is to develop a model of the system in which a combinati of various processes would produce this feature. The followi othesis, consistent with the known magnitudes of the processes with the water movements in the region, is offered as a pre- nary step in the development of our understanding of north- ern Pacific waters.

THE HYPOTHESIS

vo major premises must be recognized: (1) that the region is of net dilution; and (2) that winter temperatures in the surface rs are almost identical with year-round temperatures in the cline. It is therefore possible to account for the development niform temperatures in the halocline if the water in the upper follows trajectories corresponding to isotherms that represent geographic features of the halocline temperatures. As the waters e along such trajectories, surface dilution and winter mixing ld progressively increase the range of salinity in the halocline he surface layer became more dilute.

he hypothesis as stated above makes no implicit statement ut the direction in which the water must move along the iso- rms. If the rate of addition of fresh water is known, it should ossible to deduce from salinities in the surface layer the direction speed of the water movements. However, as will be shown r, this assumption is not strictly true.

ecause of the relatively large vertical spacings of temperature salinity observations in the halocline, it is often difficult to blish the depth limits and true structure of the layer. Conse- ntly, selection of the halocline temperature from T-S curves is n highly subjective, although the uncertainty is generally less n 1° C. In order to avoid this difficulty, temperatures for the th at which the salinity was 33.77 $^0/_{00}$ were read off for each tion examined. This particular value of salinity was selected ause of the previous studies by Tully and Dodimead (1957); , the temperatures can easily be determined when T-S diagrams available. These temperatures, then, represent conditions in the per portions of the halocline.

he temperature values based on approximately 160 stations e used to prepare Fig. 3[2], which actually represents temperature ribution at salinity 33.77 $^0/_{00}$, but the figure will be used to cribe temperatures in the halocline. Although the topography of

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Based on Lambert's Azimuthal Equal-Area projection prepared by Scripps itution of Oceanography.

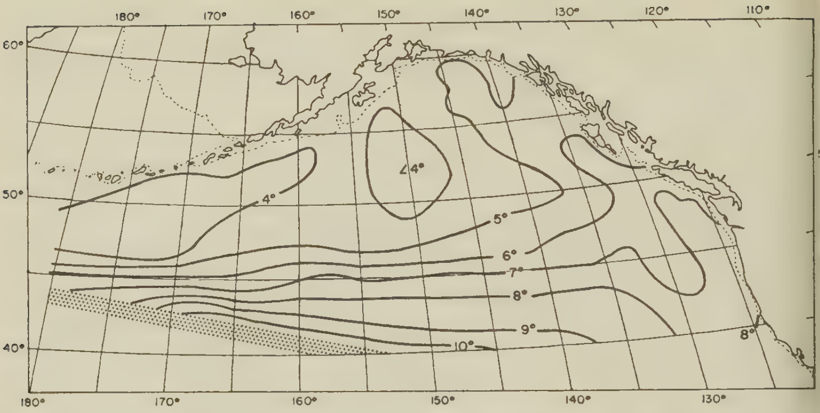
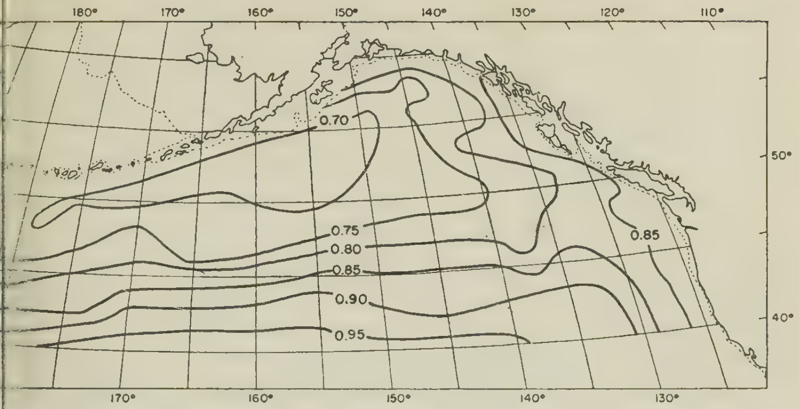


Figure 3. Temperatures in the lower part of the halocline (°C). Data actually repres
temperatures on the surface of salinity 33.77 $^0/_{00}$; for summer of 1956, except west of 157°
where data for both 1955 and 1956 were used. Dashed line indicates 100-fathom conto

the isohaline surface is not shown, in most areas it is at appro
mately 200 m, with extremes of 100 and 250 m. South of the stippl
boundary in the southwestern portion of Fig. 3, salinities excee
33.77 $^0/_{00}$ at all depths, and near the boundary the halocline is n
always present. The data used to prepare Fig. 3 were collect
during the summer of 1956 by the Pacific Oceanographic Grou
(Fisheries Research Board of Canada, 1957) and by the Universi
of Washington (Love, 1957); to the west of 157° W, observatio
made by the Pacific Oceanic Fisheries Investigations in the sur
mer of 1955 were also used (McGary, *et al.*, 1956).

If the previously stated hypothesis is correct, then the isother
in Fig. 3 should parallel the trajectories of the waters in the hal
cline. In midocean these isotherms are relatively closely space
but toward the east they spread apart. The 7° C isotherm is clo
to the parallel of 45° N to a distance of about 750 km from t
continental coast, where abrupt changes in the trends of the is
therms indicate tongue-like penetrations roughly parallel to t
coast, with the 5° and 6° isotherms extending northward and t
7° and 8° isotherms extending southward. The lowest temperature
less than 4° C, are present to the south of the Gulf of Alaska and
an east-west band south of the Aleutians. Temperatures somewh
higher than 4° C are found near the coast in the Gulf of Alaska ar
near the Aleutian Islands.



ure 4. Dynamic topography of the 200-decibar surface relative to 1000 decibars (dy- meters); for summer of 1956, except west of 157° W where data for both 1955 and were used.

order to determine the directions and speeds of circulation in halocline, Fig. 4 was prepared with data from the same stations hose used in Fig. 3. Fig. 4 shows the topography of the 200- bar surface relative to 1000 decibars. The parallelism between isotherms in Fig. 3 and the contours of dynamic topography in 4 is obvious and thus supports the hypothesis that trajectories vater in the halocline are parallel to isotherms of the halocline peratures.

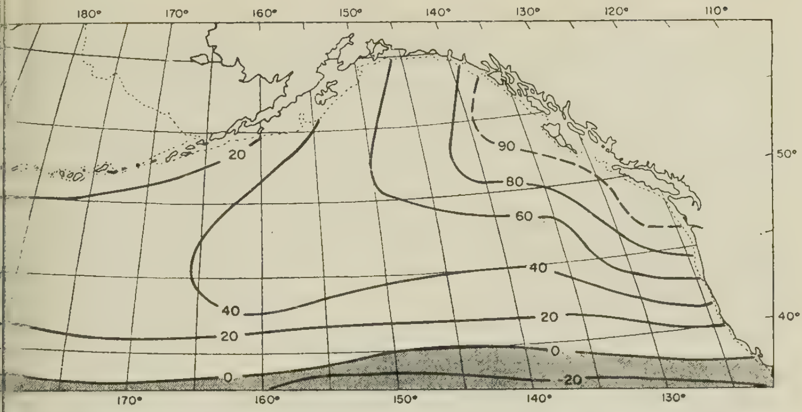
midocean the flow is generally from west to east, but the amic isobaths diverge at a distance of about 750 km from the t, the "split" occurring at about 45° N with flows north and h. The northward flow into the Gulf of Alaska tends to follow Gulf coast and to extend westward close to the Aleutian Islands. southward flow occurs off the coasts of Washington and Oregon, about 400 km off the coast there is a trough in the dynamic graphy, with northward flow near the coast. This is consistent the presence of warmer water near the coast in the southern part of the area.

he speeds of circulation indicated in Fig. 4 are relatively small. he midocean area the speeds are about 3 km/day, decreasing to than 2 km/day towards the east and in the Gulf of Alaska. The waters in the north (halocline temperatures < 4° C) have a gish circulation with speeds of less than 1 km/day. Since distances along the isotherms in Fig. 3 are of the order of seve thousand kilometers, it would require about three years for wa in the halocline to travel from 180° to 135° W, and probably equal amount of time to flow northward and then westward alo the Aleutian Islands.

The parallelism between the halocline temperatures and the namic topography of the 200-decibar surface is strong evidence support of the hypothesis because there is no *a priori* reason expect such a relationship between temperatures on an isohali surface and distribution of mass at greater depths. There are t further consequences of the hypothesis: winter temperatures in t surface layer should correspond to the halocline temperatur and the progressive dilution that can be computed from salin in the upper zone should be in agreement with the speed of mo ment and with the geographic pattern of the excess of precipitati over evaporation.

Because of probable year-to-year variations in climatic conditi in the region under consideration, too much confidence cannot placed in a comparison of data from an individual year with clima averages based on many years of observations. Comparison of Fig with the February and March data included in Robinson's (19 excellent study of temperatures in the northeastern Pacific show that north of about 45° N in midocean the temperatures in Fig were within 1° C of those in the surface layer in winter. In the G of Alaska and westward, surface temperatures were generally cool in some places by as much as 2° C. South of about 45° N the surfa temperatures were higher, the difference increasing to 3° or m at about 40° N in the area of southward flow off the California coa Rather than indicating disagreement with the hypothesis, th results are consistent with observed conditions. The water flowi northward into the Gulf of Alaska is entering higher latitudes, a it should be anticipated that winter temperatures will be col than the halocline temperatures. Dodimead (1958) has prepare diagram that shows temperature inversions of 0.5° to 2° C in t halocline in the area north of 50° N. The water turning southwa is obviously entering latitudes with higher winter temperatur hence waters in the upper part of the halocline and in the surfa layer would be expected to be warmer.

The surplus of precipitation over evaporation, shown in Fig is based on estimates of Jacobs (1951). It is seen that essentia



ure 5. Mean annual values of the surplus of precipitation over evaporation (centimet-
ear). Shaded areas indicate a deficit in precipitation. (After Jacobs, 1951).

entire area under consideration is one of net dilution, the surplus
recipitation being least in the west and south and increasing
maximum of more than 90 cm/year off the coast of British
umbia and southeastern Alaska. As waters of the upper zone
e eastward they enter regions of greater surplus of precipitation,
refore the annual rate of accumulation of fresh water should in-
se as the water approaches the coast. Attempts to use the
ckness of the freshwater layer" and the speed and direction
low along the halocline isotherms to compute the annual addi-
of fresh water have shown agreement with Fig. 5 to within a
or of two or three. This may reflect the fact that the data in
. 5 are not correct, but it is believed that this simple approach
ot valid because: (1) movements of the surface layers are not
allel to the dynamic isobaths shown in Fig. 4; and (2) conver-
ce and divergence occur in the surface layer. It is beyond the
e of this paper to discuss these aspects in the detail they deserve.
rts of dynamic topography of the surface relative to 1000 deci-
s (Dodimead, 1958) compared to Fig. 4 show differences in
, and charts of the fresh water layer in the same report support
thesis of divergence and convergence. Note that the excess of
ipitation over evaporation approaches zero in the vicinity of
boundary in the southwestern portion of Fig. 3 and that, to
south, there is a net loss of water. It is believed, therefore, that
eastward moving waters south of about 40° N are modified by

processes of evaporation and winter mixing and that the locati
and character of the oceanographic boundary region, referred to
Dodimead (1958) as the Polar Front, are largely the consequen
of flow patterns and of the relation of evaporation and precipitati

As indicated previously, it is the purpose of this paper to prese
a simple hypothesis concerning the processes that control temperatu
and salinity relationships in the upper zone in the northeaste
Pacific, and it has been pointed out that a detailed analysis wou
require a more careful evaluation of the movements and process
affecting the surface layer. Several other factors must also be tak
into account regarding water near the coast. These are:

1. Intrusion of coastal water from the south. This water has
different T-S relationship than offshore water, and, as the t
masses are mixed, the southern water modifies the simple mo
described here.
2. Divergence (or upwelling) along the coast, at least as far nor
as Vancouver Island. This upwelling is not obvious at the surfa
because of the development during summer months of a th
surface layer of dilute water that is largely a result of river ru
off. However, the surface layer is generally thin and the halocli
if present at all, is at shallow depths and is also thin.
3. River runoff that adds relatively large amounts of fresh wa
to inshore waters as they move northward and around the G
of Alaska.
4. Mixing processes in inshore waters. The strong tidal curre
characteristic of coastal waters in the area under considerati
must, in the embayments and over the Continental Shelf, contr
ute to vertical mixing in the surface zone. Consequently, t
features of the upper zone that have been described in this pa
will tend to be modified, particularly in northern areas wh
winter cooling and the formation of sea ice may produce wa
of sufficient density to sink to moderate depths. The relativ
cold waters in the halocline in the area south and west of t
Gulf of Alaska are believed to be produced in this way.

Although listed separately, these four modifying processes oper
simultaneously, and they must be taken into account in more
tailed studies of the water characteristics within several hundr
kilometers of the coast. In midocean, the thermohaline structure
the upper zone is clear-cut and uniform over long distances wh

er movements are in an eastward direction. The barrier formed
he American continent forces these waters to turn north and
h as they approach land, and this in itself will lead to unstable
patterns that favor lateral mixing. Intermixture of oceanic
rs will tend to destroy the isothermal character of the halocline,
as these mix with coastal waters there will be further trans-
ations. It seems reasonable, therefore, to consider the areas
g within several hundred kilometers off the coast as regions in
h the thermohaline structure of the upper zone will be variable
oth space and time.

DISCUSSION

an earlier study (Fleming, 1955) an attempt was made to
gnate the natural regions of the northern Pacific Ocean. Since
ively few data were then available, it is now desirable to rede-
the boundaries of such regions in the northeastern Pacific.
6 shows the principal areas under discussion. The largest is that
gnated as the Subarctic Transition, in which conditions are
ively uniform along the trajectories but in which the tempera-
and salinity characteristics change rapidly when crossing the
ent. In the southeast, water is introduced from the south by
Southern Intrusion, whose waters are modified by coastal
esses and by mixing with offshore waters in the Mixing Area.
h of about 45° the mixed waters are carried away to the south,
north of 45° the products of this mixing, further modified by
tal processes and by admixture with waters from the Subarctic
nsition, contribute to the general westward flow in the Alaskan
stal area. The large area of relatively uniform conditions and
gish circulation lying between the Alaskan Coastal area and
Subarctic Transition has been designated as the Alaskan Gyral.
e the boundaries between the areas (see Fig. 6) may vary in
tion from year to year and possibly during a year, they should
onsidered as only approximate and should be defined in terms
he circulation and of the thermohaline characteristics in the
er zone. The chief reason for designating these natural areas is
implify discussion of certain problems such as the zoogeography
he region.

he hypothesis developed in this paper provides a rational basis
oogeographic studies of plankton and smaller nekton that spend
ajor part of their existence at depths in or below the halocline.

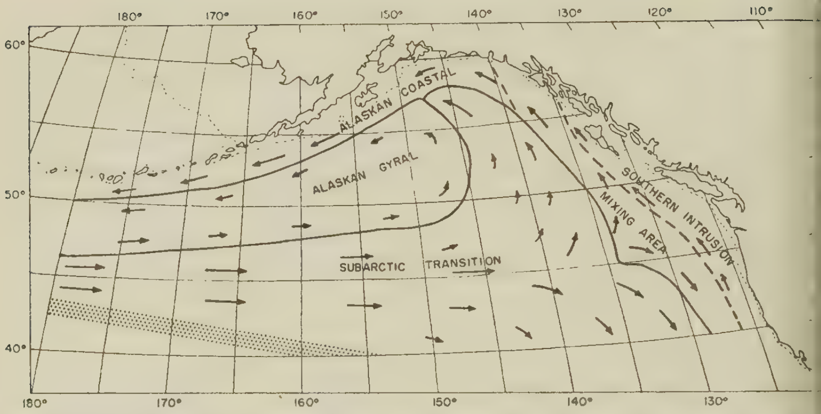


Figure 6. Natural areas in the northeastern Pacific based on the circulation and on thermohaline characteristics in the upper 200 m. Arrows show the general pattern of at about 200 m.

In the Subarctic Transition the effects of lateral mixing appear be small, therefore organisms will tend to be carried with the wa in the trajectories that parallel the halocline temperatures (Fig. or the dynamic isobaths (Fig. 4). It might be expected, therefc that in the Subarctic Transition the species composition of the lar plankton and smaller nekton should change rapidly normal to trajectories but should be uniform over long distances along trajectories. Since water movements in the halocline are relativ slow, it would require several years for a population introduced 180° W to be carried to the mixing area off the continental coa

The Southern Intrusion should be expected to introduce its o characteristic population that will either disappear gradually or the organisms tolerate the modified conditions in the Mixing Ar be carried away to the south or to the north after admixture w forms originally present in the Transition area. The Alaskan Coas area should have a mixed and probably variable species composit containing forms introduced from shallow inshore waters. The Alask Gyral should be characterized by its own homogeneous populati

This approach to a study of zoogeography, based primarily the pattern of circulation at a depth of about 200 m, indicates value of relating the regional distribution of organisms to the relationships in the upper parts of the water column. Such a pro dure has been used by Haffner (1952).

lthough temperature may be an important environmental
ure for plankton and nekton, it is difficult to decide what temp-
ures should be selected for those forms that undergo diurnal
ical migrations. Particularly during summer months, there may
arge temperature differences between the surface and depths of
ral hundred meters. It seems more rational to consider that the
or features of zoogeography of the plankton and nekton are
ted to the pattern of circulation. If, as in the northeastern
ific, there is a relationship between circulation pattern and
perature in the halocline and, in general, with winter surface
peratures, a coincidental correlation of these temperatures with
zoogeographic features might be expected.

is obvious that the concepts presented in this paper should be
ed more thoroughly. The study should be extended to the west
to the southeast to obtain a more complete picture of the
racteristics of the halocline and of the processes that produce it.
mentioned earlier, more detailed studies should also be made of
convergence and divergence in the surface layer. It is essential
t field measurements be made to determine more precisely the
ucture of the halocline. These measurements should not be limited
temperature and salinity but should include dissolved oxygen
possibly other properties such as inorganic phosphate and the
er biologically-affected substances. It is usually possible from
observed properties to determine the depth of mixing and the
racteristics associated with the water produced during the
vious winter. If, as stipulated by the hypothesis, the halocline
he result of a number of years of progressive dilution, then some
dence of the water produced in previous winters should be ob-
ned from such detailed studies. It is possible that the gradient
salinity in the halocline (and the same is probably true for dis-
ved oxygen) is not uniform but is actually of a stair-step structure,
"risers" corresponding to the water produced each winter and
"treads" to the progressive annual dilution.

SUMMARY

. The thermohaline structure of the northeastern Pacific (north
about 40° N) is characterized by a quasi-isothermal halocline
out 100 m thick and located below a surface layer about 100 m
ck.

2. In midocean the temperature in the halocline increases fr
about 4° C at 50° N to 10° C at about 40° N. From west to ea
temperatures are uniform to within about 750 km of the coa
where the isotherms tend to parallel the coast.

3. The dynamic topography of the 200-decibar surface relati
to 1000 decibars indicates flow in the halocline parallel to the i
therms of the halocline temperatures.

4. According to the proposed hypothesis, the halocline is form
by progressive dilution over a period of several years, the wat
moves along trajectories parallel to the halocline isotherms, a
each winter the mixing produces a surface layer where the tem
erature is that of the halocline and where the salinity is low
than that of the deep part of the halocline. Where the flow h
a north-south component, temperatures in the halocline are n
uniform.

5. The persistence of the halocline structure in the Subarc
Transition implies that lateral mixing is of negligible importance
a modifying process in the upper 200 m.

6. On the basis of thermohaline characteristics in the upper zo
of the pattern of circulation, and of the hypothesis concerning t
life history of the waters, certain natural regions are designat
that may provide the basis for zoogeographic studies.

ACKNOWLEDGMENTS

This token of my respect and affection is presented as a tribu
to my distinguished colleague Professor Thomas Gordon Thomps
on his seventieth birthday.

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Dianne Heggarty and Mr. Cuthbert M. Love was made possible
support from the Office of Naval Research under Contract Nonr-4
(10), Project 083-012.

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HYDROGRAPHIC AND BIOLOGICAL INVESTIGATIONS IN OSLOFJORD BY MEANS OF THE DENSIGRAPH AND TH OXYMETER

By

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Oslofjord, which runs in a north-south direction, is about 100 k long from the open sea to Oslo Harbour. About 30 km south Oslo, where the fjord narrows at Drøbak, there is a threshold wi a depth of 19.5 m. Inside (that is, north of this threshold) the ma mum depths are 150 m.

Oslofjord is characterized by highly stratified water mass especially during summer. At that time of year a heavy prima and secondary pollution by sewage from Oslo influences the amou of dissolved oxygen in the water so that sometimes the oxyg content varies between saturation (or even supersaturation) in t surface layers to little or no oxygen at 10 to 20 m. With these hydr graphic conditions, the usual methods of water sampling and anal sis at specific depths do not provide satisfactory information. Th it has been necessary to seek methods for recording continuous the variations that exist.

Some years ago we succeeded in developing two types of appar tus: the densigraph and the oxymeter. The densigraph (Føyn, 195 measures the density, *in situ*, by means of a balancing liquid a connecting tubes. The level of the liquid is photographed contin ously on a plate that is moved by water pressure as the apparat descends. The plate, when developed, then provides a curve th shows the variations in density with depth. The oxymeter (Føy 1955), which measures the oxygen content of water electrically, fitted with an insulated cable that is connected to a recorder the boat. (Previously it was connected to a microammeter). T oxygen curve is recorded directly on paper that is moved by ele trical pulses from the meter wheel. Since the paper moves one mil meter for each meter of descent or ascent of the apparatus, th instrument thus provides a continuous oxygen curve as it mov down and up through the water. Thus the data obtained on t down are checked on the way up, as shown in Fig. 1. Often inct oxygen maxima and minima are registered, and it is there- possible during a short time to determine the depths which may f special interest in hydrographic and biological work.

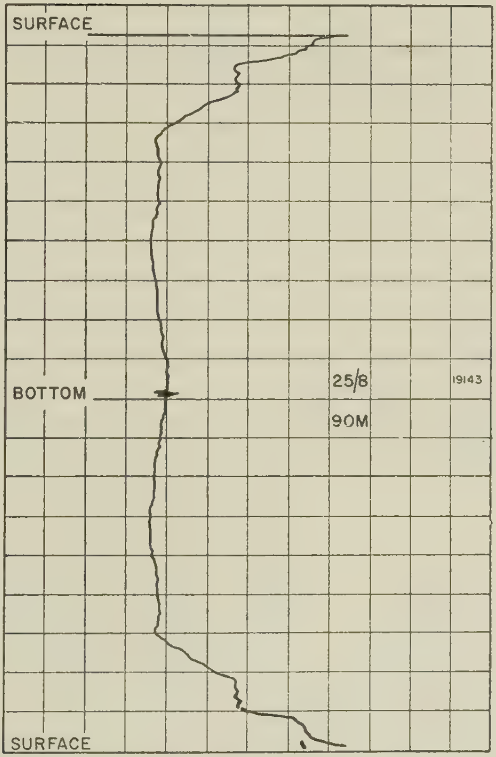


Figure 1. An oxygen curve recorded by the oxymeter.

Jse of these instruments in Oslofjord has given new details of nditions there. Fig. 2 shows density and oxygen curves obtained August 1954 at two stations in the fjord, one about 10 km south the Drøbak threshold and another north of the threshold. The nsity curve (solid line) shows that a surface layer of relatively nt water floats on top of the heavy bottom water. The discontin- y layer dividing these water masses has such a sharp increase density with depth that the density curve slopes only slightly,

giving a variation in σ_t of several units per meter. The oxyg
curves (dotted lines), especially the one from the station north
the Drøbak threshold, shows a remarkable oxygen minimum exac
in the discontinuity layer. This probably results from sewage dispo

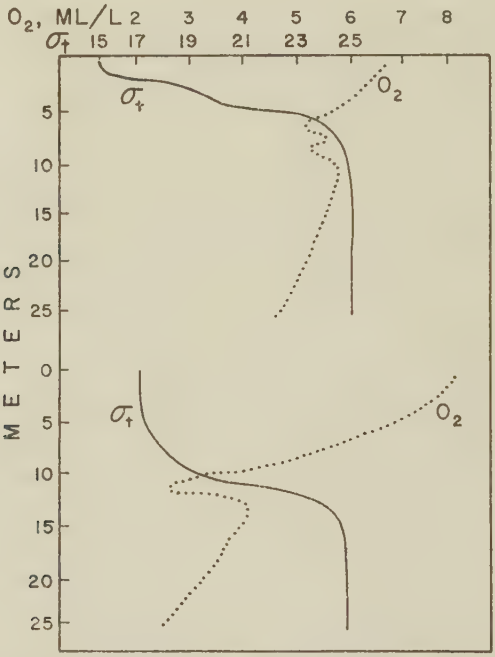


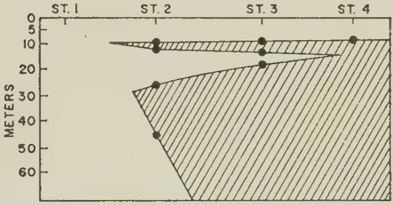
Figure 2. Density and oxygen curves obtained in August 1954 at two stations in O
fjord, one about 10 km south of the Drøbak threshold, the other north of the thresh
Solid lines, density; dotted lines, oxygen.

in the fjord, since fertilizing elements from pollution induce a hea
production of algae in the upper layer during summer. As orga
particles sink, they accumulate in the discontinuity layer, whe
the density increases rapidly. This layer, then, acts as a false b
tom where decomposition and oxidation take place with a resulta
decrease in oxygen content.

Such great variations in oxygen content as are observed in Os
fjord will naturally influence biological conditions there. For
ample, Sundnes (1957) found that codfish had a critical level at
oxygen content of 2.7 ml O_2/l. Under natural conditions this le

ht be lower than that, but north of Drøbak in the inner part of fjord the oxygen content may often go far below 2.7 ml/l.

ig. 3 illustrates the distribution of oxygen north of Drøbak in ust 1957. Isolines for the value 2.7 ml O_2/l are drawn from St. 1, t 25 km below Oslo Harbour, to St. 4, about 10 km inside the



ure 3. Oxygen conditions in Oslofjord north of the Drøbak threshold in August 1957. hed area shows where density was less than 2.7 ml/l.

bour. Oxygen values of less than 2.7 ml/l are hatched. Thus the stration shows the areas and depths where codfish might find er favorable or unfavorable conditions. Obviously it is of interest fishermen to know just where low oxygen concentrations are ly to be found, since they can then more profitably devote their rts to other areas where the fish are likely to be living.

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DETERMINATION OF OPAL IN MARINE SEDIMENTS

By

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ABSTRACT

The opal contents of recent marine sediments are ascertained by conversion the opal to crystobalite by heating and by a subsequent quantitative x-ray diffr tion analysis of the crystobalite. An opal stratigraphy is evident in Bering Sea dep its. Further, the opal concentrations appear to be covariant with barium, an ment previously suggested as indicative of biological productivity in overlying wa masses.

INTRODUCTION

One of the principal constituents in some marine sediments opal, a highly disordered form of silicon dioxide, which genera contains less than 12 % water. This opal originates in the pla and animal life of the sea as frustules of diatoms or as skeletal mains of such organisms as radiolaria and sponges. There is evidence for the inorganic deposition of opal in the marine enviro ment. Although siliceous oozes and siliceous muds are defined terms of the amount of opal present, there have been no dir methods of assay other than that of visual estimation. This situati prompted a survey of possible analytical techniques. Profess William D. Johns of Washington University, St. Louis, suggest converting the opal to crystobalite by heating and carrying throu a quantitative x-ray diffraction analysis of the crystobalite. T paper covers preliminary results of experiments that consider su a method.

EXPERIMENTAL

General Method. A calcium carbonate-free marine sediment sam of 0.5–1.5 g, ground to a fine powder (100–200 mesh), was plac in a platinum crucible and heated at 900° C for four hours. T height of the resultant 4.04 *Å* diffraction peak of crystobalite w determined on a Norelco X-Ray Diffraction Spectrometer at 35 *K*

20 MA, using copper K_α radiation. In order to secure the most oducible results, known amounts of opal (10 and 20 %, by weight) added to a second and third sample respectively, and these ples were then heated simultaneously; peak height determina- were subsequently made. The opal content of the sample found from the best fit to the following equations, where x is original percentage of opal in the sediment, k a proportionality or, and P_n the intensity of the 4.04 Å line obtained in samples an added percentage n of crystobalite:

$$\begin{aligned} &(a) & x &= k\,P_0\,, \\ &(b) & x+10 &= k\,P_{10}\,, \\ &(c) & x+20 &= k\,P_{20}\,. \end{aligned}$$

ote 1. Opal standards. Sponge spicules, obtained from live nals taken from Mission Bay, San Diego, California, constituted primary opal standard. The sponges, treated with a mixture ne part nitric and one part perchloric acid, were heated to a perature approaching the boiling point of the mixture to de- y the organic phases and subsequently cooled. The residue of ules was washed repeatedly with distilled water, dried and und to a 100–200 mesh powder.

Note 2. The temperature of 900° C and the heating time of four rs were arrived at empirically. Typical conversion data are given Table I for diatomaceous earth from the Monterey formation at os Verdes, California.

BLE I. Effect of Temperature and Time of Heating on the Conversion of Opal to Crystobalite

Heating Time (hrs)	*Heating Temperature (° C)*	*Peak Height of Crystobalite (arbitrary units)*
1	800	5
2	800	5
4	800	13
1	900	28
2	900	28
4	900	31
8	900	30
	Untreated Control	0

Note 3. Inasmuch as calcium carbonate and silicon dioxide inter- at the heating temperature to form the calcium silicate woll-

astonite, samples containing calcium carbonate were initially wash
with 0.01 N hydrochloric acid, rinsed with distilled water, and dri
before heating.

Note 4. Heating to or above 1000° produced glassy materia
and the resultant diffraction intensity of crystobalite was not
high as at 900° C and was not in general reproducible.

TABLE II. Typical Opal Runs on a Sediment Sample. Sample from Beri
Sea, Chinook 9 Core Scrapings

(a)	x = k 23	(a–b)	k = 10/23 = 0.43
(b)	x + 10 = k 46	(a–c)	k = 20/43.5 = 0.46
(c)	x + 20 = k 66.5	(b–c)	k = 10/20.5 = 0.49
	Average k = 0.46		Percent opal in sample is 11 %.

Note 5. In the initial work, uric acid was added to the samp
(following heating) as an internal standard. However, this techniq
was abandoned in favor of the "use of incremental amounts of o
as internal standards" because it was found that the amount

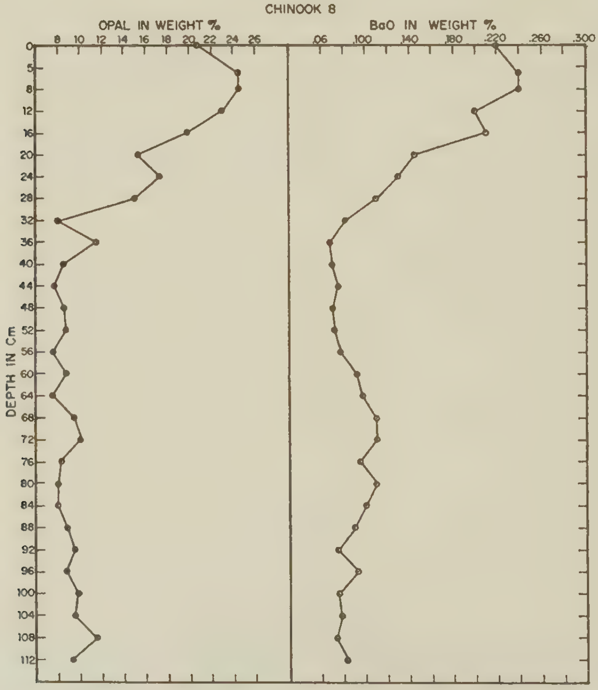
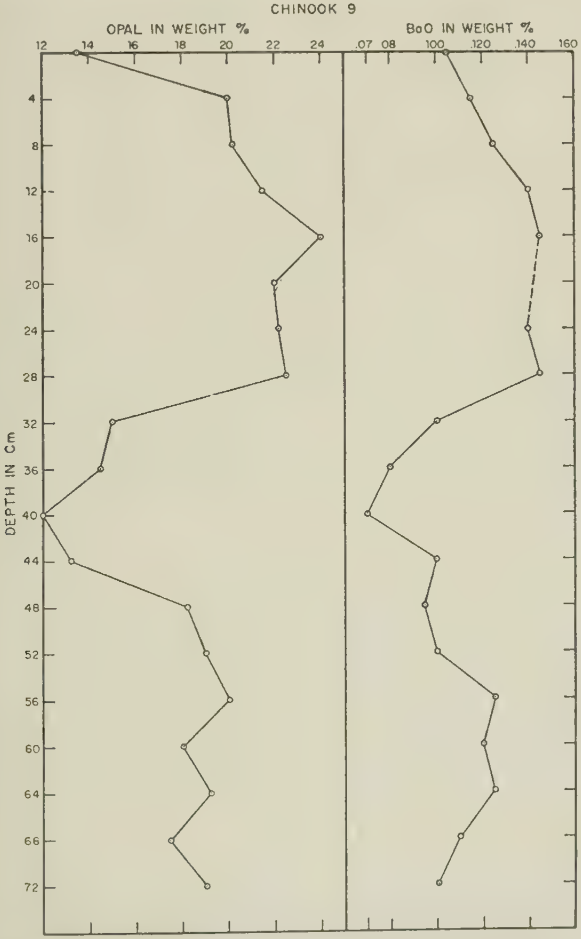


Figure 1. Opal and barium oxide concentrations in Chinook 8, from Lat. 53°01.5′
Long. 176°15.0′ W at a depth of 3660 m.

ersion was a function of any previous chemical treatments the ples had received. Washing with HCl, NH_4Cl or distilled water ced the intensity of the resultant crystobalite peak and/or dened the peak. These disturbances, introduced by such wash- were eliminated by introduction of the "incremental opal" he samples before washing.

ote 6. The reproducibility of the results appears to be of the of ± 10 %. Table II gives illustrative data on a typical set plicate runs. The lower limit of detection was 2 % opal.



gure 2. Opal and barium oxide concentrations in Chinook 9, from Lat. 52°25.2′ N, 176°24.5′ W at a depth of 3440 m.

RESULTS

The depth distribution of opal in a pair of diatomaceous sedim cores from the Bering Sea, Chinook 8 and Chinook 9, is shown Figs. 1 and 2. In both cores, obtained not far from one anot an opal stratigraphy appears. There is a marked decrease of o with depth, with values of 20 % by weight at the surface and 10–15 % at about 30 cm. In Chinook 9 there is a clear incre again at about 48 cm. The significance of such concentration chan is not as yet understood.

Of interest, however, is the possibility of a relationship betw the opal, presumed to represent in these cores a measure of biogenous contribution to the sediment, and barium, an elem believed to be related to the productivity of an area (Goldberg Arrhenius, 1958). Figs. 1 and 2 clearly demonstrate the covaria between barium and opal. The barium values were determined emission spectroscopy (Goldberg and Arrhenius, 1958).

Since concentrations of barium are markedly higher in pela sediments below productive oceanic areas than in either the careous or siliceous parts or in the dried organic phases of marine biosphere, barium is probably accumulated in deep deposits through chemical reactions involving organic debris. H barium contents are associated with both siliceous and calcare deposits. One possibility may be the release of high concentrati of sulphate ion, resulting from oxidation of organically bou sulphur, in such deposits with a consequential precipitation barium sulphate (Arrhenius, 1959).

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NTROL OF SEDIMENTATION AND BOTTOM CONFIGURATION BY CONVECTION CURRENTS, LAKE WASHINGTON, WASHINGTON[1]

BY

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ABSTRACT

Lake Washington near Seattle occupies a deep narrow trough sculptured by the
hon ice sheet, the last continental glacier to invade the Seattle area. Extending
ng the center of the trough is a broad ridge that stands 5 to 30 feet above narrow
leys on either side. Thus, the trough in cross-section is W-shaped rather than
haped, as are most glacial valleys. The sediments in the trough consist of
e clay, locally more than 100 feet thick, overlain by limnic peat or gyttja 5 to
feet thick. The blue clay consists of rock flour of meltwater origin and the limnic
t consists of planktonic organisms that began to accumulate following the melt-
er stage. Within the limnic peat are a layer of volcanic ash and an overlying
er of varved peat, each about 2 inches thick. Radiocarbon analyses place the
of the ash at 6,700 years and that of the blue-clay peat contact at 13,650 years.
estimated age of the varved layer is 5,000 years. Core profiles across the lake
w that the trough was U-shaped at the close of blue-clay deposition and that
W-shaped profile had approximately its present configuration at the time of
ash fall. Investigations of the lake-temperature structure, together with certain
inctive features of the lake topography and sediments, point to convection
rents as being the agents responsible for the observed inequalities in limnic-peat
imentation which, in turn, account for the unusual W-shaped configuration of
trough floor.

Based on investigations conducted at the University of Washington. Contri-
ion No. 221, from the Department of Oceanography, University of Washington.
lication was supported in part by the Agnes H. Anderson Fund of the Uni-
sity of Washington.

INTRODUCTION

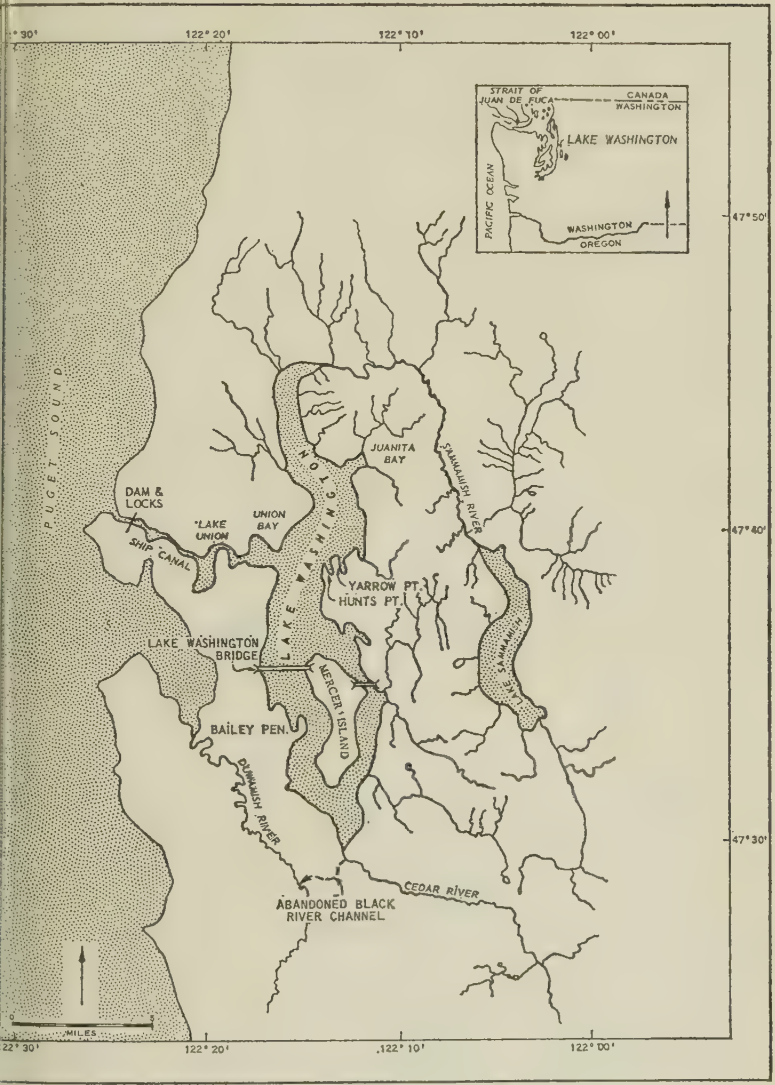
Lake Washington, a deep elongate body of water that borde Seattle on the east (Fig. 1), is 18.5 miles long, averages 1.5 mil in width, and has a mean depth of 108 feet. In its southern part Mercer Island. The lake stands 20.6 feet above mean low low ti in Puget Sound, to which it is connected via Lake Union and t man-made Lake Washington Ship Canal. This canal, approximate 8 miles long, is terminated at its western end by a dam and two lock

Prior to completion of the canal in 1916, the lake stood 9 fe higher than it is now (U.S. Army Corps of Engineers, 1939). At th time the only appreciable inflow into it was from the Sammami River on the north. The only outflow was through the Black Riv on the south, which, after receiving the drainage of the tributa Cedar River about one-half mile south of the lake, discharged i water through the Duwamish River into Puget Sound. With co pletion of the canal and a lowering of the lake surface to its prese level, Black River was left dry and Cedar River was diverted in Lake Washington. Thus the lake now has two principal sources inflow, Sammamish and Cedar Rivers. All discharge is controll through the Ship Canal.

Lake Washington, like Puget Sound and neighboring Lake Sa mamish, lies in an unfilled remnant of a relict drainage syste sculptured and modified by the Vashon ice sheet, the last continent glacier to invade the Seattle area (Bretz, 1913; Stark and Mullineau 1950). The lake basin lies entirely within glacial drift and outwa except in the vicinity of Bailey Peninsula west of Mercer Isla where marine sediments of Oligocene age are exposed (Weave 1916). Except where indented by modern streams or remna glacial valleys, the glacial deposits rise in precipitous cliffs fro the lake shore to altitudes of 300 feet or more.

Bretz (1913) concluded that, with the withdrawal of the Vash ice sheet from western Washington, Lake Washington and Pug Sound were connected first as part of a large glacial lake and lat as an arm of the sea. The latter event was occasioned by cleari of ice from the Strait of Juan de Fuca which permitted invasi of both Puget Sound and the Lake Washington basin by mari waters.

To investigate whether the lake had in fact undergone such marine phase in postglacial time and to develop the stratigrap


°30'
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STRAIT OF JUAN DE FUCA
CANADA
WASHINGTON
LAKE WASHINGTON
PACIFIC OCEAN
WASHINGTON
OREGON
47°50'
47°40'
47°30'
PUGET SOUND
DAM & LOCKS
SHIP CANAL
LAKE UNION
UNION BAY
LAKE WASHINGTON
JUANITA BAY
SAMMAMISH RIVER
YARROW PT.
HUNTS PT.
LAKE WASHINGTON BRIDGE
MERCER ISLAND
LAKE SAMMAMISH
BAILEY PEN.
DUWAMISH RIVER
CEDAR RIVER
ABANDONED BLACK RIVER CHANNEL
0
5
MILES
22° 30'
122° 20'
122° 10'
122° 00'

Figure 1. Lake Washington and vicinity.

region of continuous deposition following the retreat of Vashon n intensive study was made of the lake topography and bottom sediments. In the course of this work, echograms over more than 200 miles of sounding traverse were obtained, and from th a topographic map was constructed. In addition, representat sections of sediments deposited since the withdrawal of ice from lake basin were collected by means of a long piston corer of type designed by Kullenberg (1947). Altogether, 30 cores, rang in length from 5 to 72 feet and averaging about 29 feet, were tal from the bottom sediments.

From preliminary examination of both topography and bott deposits, it became apparent early in the field study that the ra of sedimentation differed appreciably even over short distances the bottom and that these inequalities were probably relate convective circulation. To test this hypothesis, a limited stud the lake-temperature structure was made, and model studies lating convective circulation in the lake were initiated. Results these investigations are gratifying, for they appear to explain observed inequalities in sedimentation which, in turn, account the unusual configuration of the lake floor.

This report deals only with those parts of the investigation wh bear on the role of convection currents in sedimentation and sculpturing the lake bottom. A more detailed account of all pha of the study will be presented in a later report (Gould and Budin in preparation).

TOPOGRAPHY

The bottom topography consists of three principal elements wave-cut bench, a steep marginal slope, and a deep floor (Fig. The wave-cut bench extends from the pre-1916 level, 9 feet ab the present lake surface, to a depth of about 40 feet. In its s aqueous portion, the bench is generally less than 600 feet w except where the shore is indented by the embayed mouths glacial valleys. Most notable of these are Union, Juanita, Meyd bauer, and Andrews Bays. It is in these regions and at the mou of the Sammamish and Cedar Rivers that the shore configurat was changed most markedly by lowering of the surface in 1 In other areas, as off the northern end of Mercer Island (in Fairweather-Yarrow Point region) and south of Juanita Po glacially sculptured ridges and intervening valleys which conti underwater for appreciable distances add to the shallow areas the lake.

At its outer edge, the bench and associated shallow areas

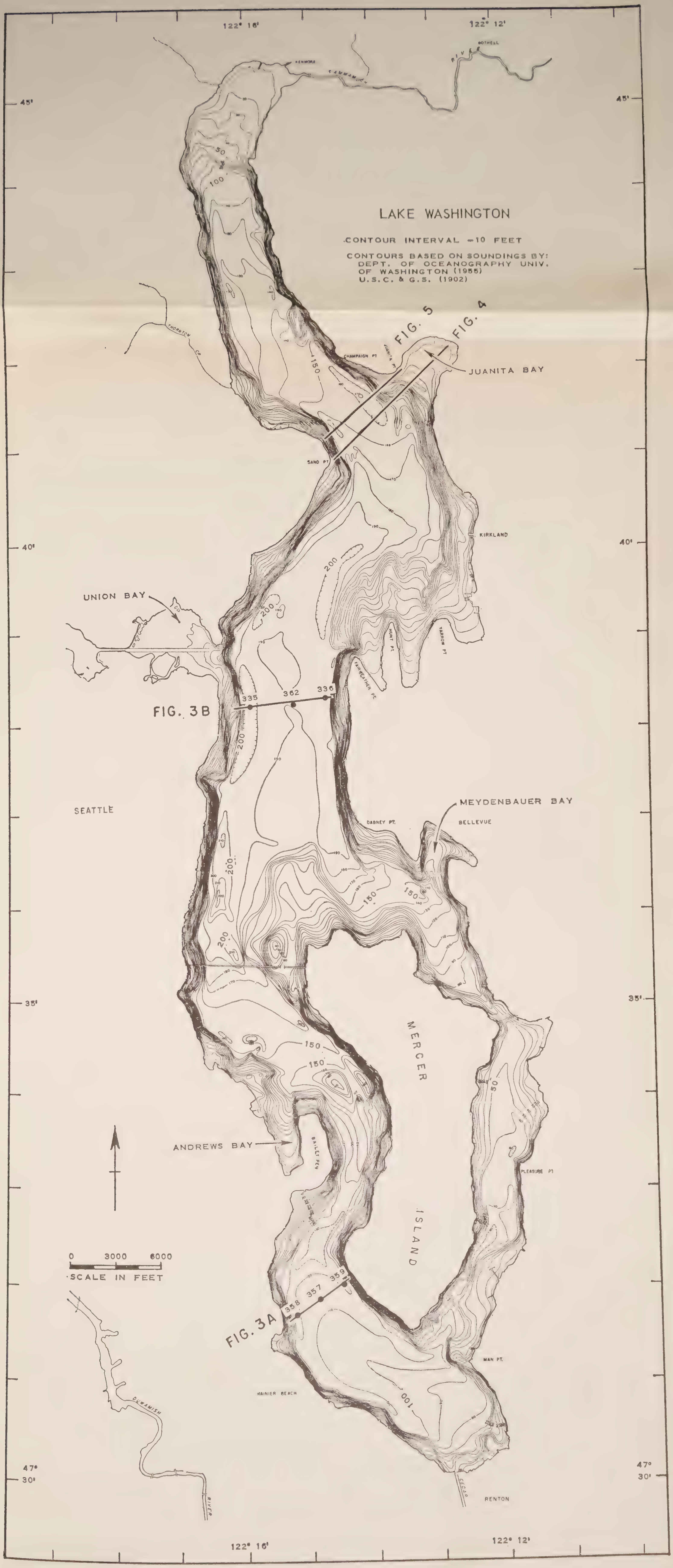

122° 16'
122° 12'
45'
40'
35'
47° 30'
LAKE WASHINGTON
CONTOUR INTERVAL – 10 FEET
CONTOURS BASED ON SOUNDINGS BY:
DEPT. OF OCEANOGRAPHY UNIV. OF WASHINGTON (1955)
U.S.C. & G.S. (1902)
KENMORE
SAMMAMISH RIVER
BOTHELL
THORNTON CR.
CHAMPAIGN PT
JUANITA PT
FIG. 5
FIG. 4
JUANITA BAY
SAND PT
KIRKLAND
UNION BAY
HUNT PT.
YARROW PT
FAIRWEATHER PT.
FIG. 3B
335
362
336
SEATTLE
MEYDENBAUER BAY
DABNEY PT.
BELLEVUE
MERCER
ISLAND
ANDREWS BAY
BAILEY PEN
PLEASURE PT
FIG. 3A
358
357
359
MAN PT.
RAINIER BEACH
DUWAMISH RIVER
CEDAR
RENTON
0 3000 6000
SCALE IN FEET
50
100
150
200

Figure 2. Lake Washington bottom topography. All depths are referred to the lake surface which lies 20.6 feet above mean low low water in Puget Sound.

ninated by the steep marginal slope that descends abruptly to
trough floor, which in places exceeds 200 feet in depth and
rages about a mile in width. The declivity of this slope ranges
n 6 to 24 degrees and averages about 14 degrees.

xtending along the deep floor of the lake is a broad ridge that
ends to more than 30 feet above narrow valleys which lie at the
of the steep marginal slopes. Thus, the lake bottom in cross-
ion has a subdued W-shape rather than the U-shape which is
racteristic of most glacial troughs. This unusual configuration
feature also of the deep tributary arm between Mercer Island
Meydenbauer Bay.

he echogram, Fig. 5, depicts a typical cross-section of the lake
tom. The W-shape characterizes not only the present bottom
also a sub-bottom reflecting layer about 20 feet beneath the
floor; upon subsequent coring this was found to consist of a
ich bed of white volcanic ash. It is apparent from the W-shape
he ash layer that the deep lake floor, except for its greater depth,
approximately its present configuration at the time of ash
osition.

Within the marginal valleys are several closed depressions with
toms lying generally less than 10 feet below sill depths. Signif-
ntly, the largest depressions lie adjacent to steep side slopes
rdering the most extensive shallow areas of the lake, including
ion Bay, the Fairweather Point area, Juanita Bay, Meydenbauer
y, and the area northwest of Mercer Island. The depressions off
ion Bay, Meydenbauer Bay, and possibly off Fairweather Point
pear to be continuations of small canyons that indent the slope
l head in these shallow areas.

The only interruption of the central ridge in the main body of
lake occurs east of Bailey Peninsula where the marginal valleys
rge to form isolated basins, the deepest of which lies 43 feet be-
the top of the sill and 190 feet beneath the water surface.

SEDIMENTS

Since preliminary studies have indicated that most of the sedi-
nts deposited in Lake Washington following withdrawal of
shon ice lie in the deep central trough, investigation of the depo-
has been confined to those of this area. The 30 cores obtained
located on 11 east-west sections which lie between Sammamish

River on the north and Cedar River on the south. In most sectic one core was taken from the central ridge and one from the vall on either side. Although no cores were collected from the shal margins and steep slopes bordering the trough, it is apparent fr studies of Stark and Mullineaux (1950) and from borings m available by the State of Washington Toll Bridge Authority t these areas are underlain chiefly by pre-Vashon sediments i which the Lake Washington basin was cut. Thus the post-Vasl deposits occur as valley fill flanked by these older beds.

Except for deltaic deposits encountered near the mouths of Sammamish and Cedar Rivers, the sequence of sediments in sections is essentially the same. This sequence consists of gla blue clay at the base overlain by limnic peat (Voss, 1934) or gyt (Twenhofel, 1939), which, in the sections of Fig. 3, ranges from to 41 feet in thickness. Elsewhere the thickness of the limnic p ranges from 5 to 55 feet. Although the blue clay was penetrated our borings to a maximum depth of 35 feet below the base of limnic peat and to a depth of 100 feet in borings of the State Washington Toll Bridge Authority, its base was not reached.

The blue clay consists of glacial rock flour of meltwater orig whereas the limnic peat consists of freshwater planktonic organis (mainly diatoms) and decomposable organic matter which beg to accumulate following the meltwater stage.

In two cores a thin layer of marine molluscs and foraminif contained within the blue clay at depths of 4 to 13 feet bene the base of the limnic peat provides the only evidence of an ea postglacial marine phase for Lake Washington. The association this fauna with thin lenses of sand within the clay suggests tl both the fauna and the sand were displaced by slumping from sh lower depths. Whether slumping occurred during marine occupan of the basin or at some later time is unknown. A search of the cl for fauna above and below the marine fossil bed sheds little lig on the problem. The clay below the fossil zone is barren, where the clay above contains a sparse freshwater diatom assembla Uniform low salinities of interstitial water in the clay both abo and below the marine shell layer suggest, however, that freshwa conditions prevailed in the basin at the time of slumping and th marine occupancy preceded deposition of the deepest clay penetrat which, as previously stated, lies 100 feet beneath the base of t limnic peat sequence.

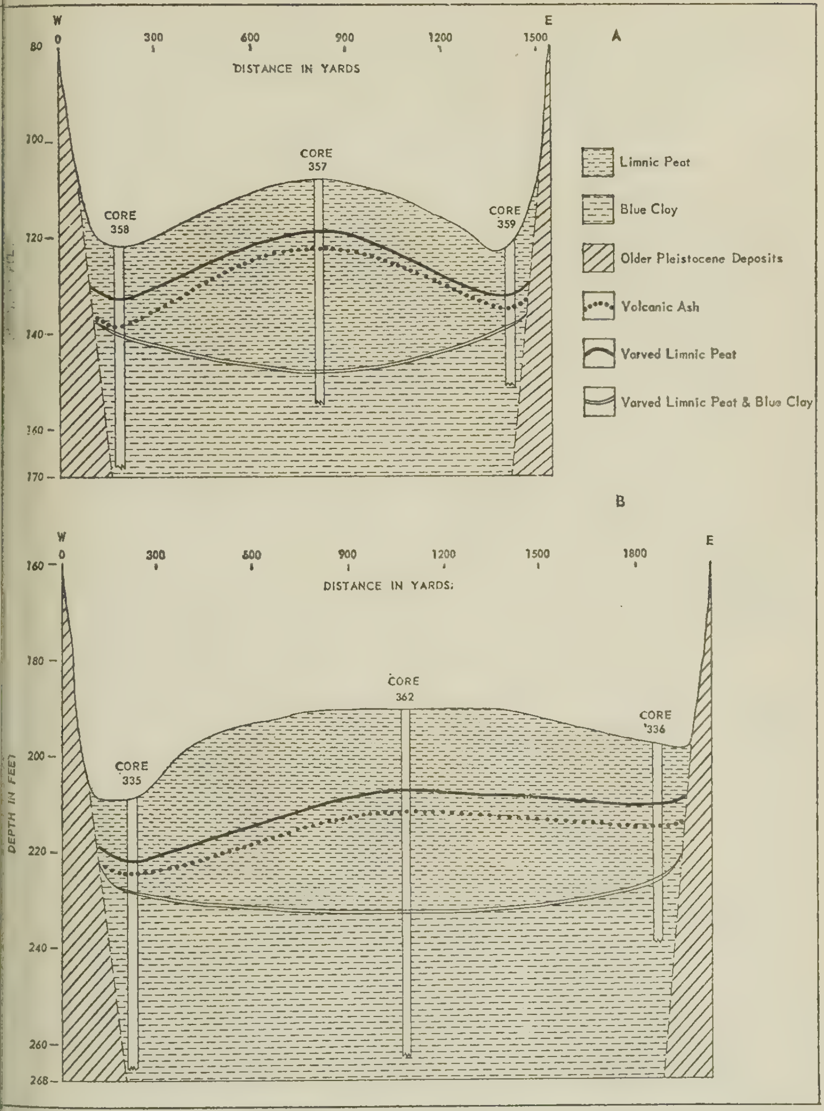

A
W
E
0
300
600
900
1200
1500
DISTANCE IN YARDS
80
100
120
140
160
170
CORE 357
CORE 358
CORE 359
Limnic Peat
Blue Clay
Older Pleistocene Deposits
Volcanic Ash
Varved Limnic Peat
Varved Limnic Peat & Blue Clay
B
W
E
0
300
600
900
1200
1500
1800
DISTANCE IN YARDS
160
180
200
220
240
260
268
DEPTH IN FEET
CORE 362
CORE 335
CORE 336

Figure 3. Cross-sections showing stratigraphic sequence of the trough fill. Thickness of h and varved layers not to scale. For location of sections, see Fig. 2.

The contact between the blue clay and overlying peat is invaria marked by a varved layer about 12 inches thick which represe the transition from meltwater to planktonic sedimentation. E varve consists of two layers (or laminae), one of diatoms and other of clay. The diatoms were evidently deposited in wi whereas the clay was laid down during summer thaw of the rece Vashon ice sheet. A count of the varves shows that the perio transition lasted about 200 years.

Within the limnic peat are the layer of white volcanic ash a layer of varved peat, each about 2 inches thick, which in cr section (Fig. 3) have the same subdued W-shaped configuration the present bottom. The varved layer, lying 3 to 4 feet above ash, consists of light-colored laminae high in diatoms, with in vening layers of dark decomposable organic material. The li layers evidently reflect deposition during the spring of the y when the diatom population was most abundant (Scheffer Robinson, 1939; Anderson, 1954), whereas the dark layers repres deposition in other seasons. A count of the varves indicates a positional interval of about 60 years.

Elsewhere the limnic peat has no discernible stratification. I characterized instead by a splotchy, mottled appearance impar by mixed patches of light and dark peat. The marked similarity composition of these patches to the alternating layers of the var section leads to the conclusion that the mottled structure was p duced by erosion and redeposition of peat laid down initially varves.

POSTGLACIAL HISTORY

In brief, the Lake Washington sediments record the follow postglacial events:

1. Occupancy by marine water of the lake basin and Puget Sou to which the basin was freely connected, upon clearing of ice fr the Strait of Juan de Fuca. This event, recorded by the displa marine shell bed in the blue clay, evidently preceded deposition the deepest clay penetrated.

2. Conversion of the basin from an arm of Puget Sound to freshwater lake in which the meltwater blue-clay sequence deposited. Isolation of the lake basin from Puget Sound presuma resulted from damming of the basin at its southern end by de building.

. Cessation of meltwater deposition and the beginning of pre- inantly organic sedimentation as represented by the transition n blue clay to limnic peat.

Continued organic sedimentation to the present time, inter- ted by a fall of volcanic ash represented by the ash layer at -depth in the limnic peat sequence.

adiocarbon dating of peat from the blue clay-peat contact places ge of the terminal meltwater stage at 13,650 years. The ash , as reported by Rigg and Gould (1957), was laid down 6,700 s ago from an eruption of Glacier Peak, a Cascade volcano ed about 63 miles northeast of the lake. By interpolation, the ved peat layer a few feet above the ash was deposited about 0 years ago.

ORIGIN OF THE W-SHAPED TROUGH

he sections of Fig. 3 show clearly that the floor of the Lake shington trough was flat or U-shaped at the end of blue-clay osition and that the present subdued W-shape has resulted m subsequent inequalities in limnic peat sedimentation. The tral ridge and narrow valleys were well established at the time ash deposition. In fact, it was between the end of the blue-clay se and the ash fall that the ridge grew most rapidly. It is ap- rent also that the W-shaped section at the time of the ash fall l reached a state of approximate equilibrium with the process t produced it and that this equilibrium condition has been intained to the present time.

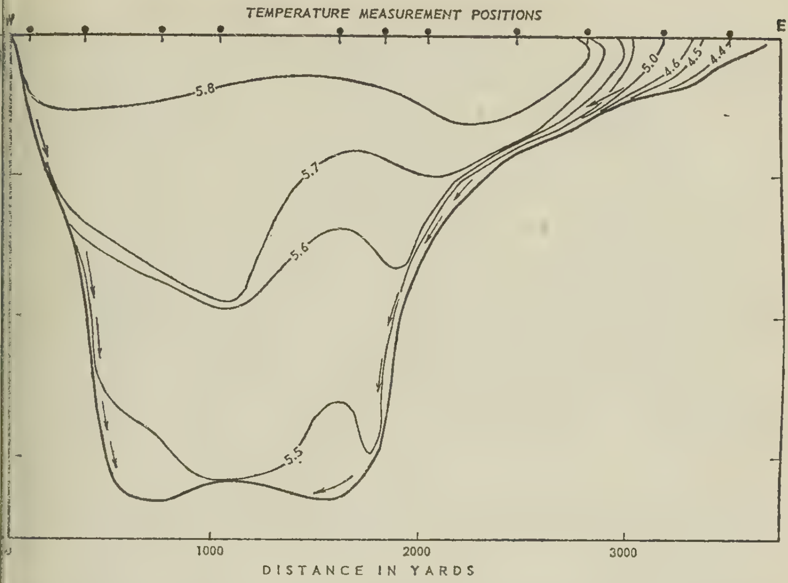
n an attempt to identify the process or processes responsible for W-shape, the following three possibilities were entertained: density currents from entering streams, (2) deep rotary circu- ion resulting from wind action, and (3) convection currents. nsity currents from inflowing streams cannot be considered iously because such currents, if they actually exist in the lake, uld produce or follow a central valley like that of the blue-clay face instead of producing the marginal valleys observed. Rotary d-induced circulation does not appear a likely explanation either. ch circulation is confined chiefly to the upper surface layers of ter, and it is doubtful that wind-induced currents, if they extend depth, would be of sufficient velocity to produce the valleys.

Of the three possibilities, convection currents appear to pro the most likely explanation. As shown by Scheffer and Robi (1939), in general terms the water of Lake Washington overt annually, beginning in December and lasting through Februar March. Water cooled at the surface during this period sinks, some mixing, towards the lake floor and is replaced by war water from below. This process of convection takes place to s extent over the entire lake surface; however, a shallow colum water is cooled more quickly than a deep one with the result water in the bays and along the shallow margins of the lake c and increases in density more rapidly than the upper layer midlake. This denser water tends to flow from the peripher the edge of the steep marginal slope and thence down to the tro floor. As a result, a considerable volume of water at veloc higher than those of convection currents elsewhere in the lake n flow down the marginal slopes.

To determine whether such concentrated flow does in fact t place down the marginal slopes, a study of the lake-tempera structure along a line of section from Sand Point to Juanita was made during a period of intense surface cooling in Janu 1956. Results of this survey, as illustrated by isotherms in Fig show clearly that such a flow does occur. At the time of the sur the coldest water, ranging from 4.4° to about 5.0° C, was situa in the shallow Juanita embayment. Due to intense cooling to the shallow bottom, this cold water could not be replaced warmer water from below. Consequently there was a much gre flow of cold water, as shown by the packing of isotherms, down steep marginal slope leading from Juanita Bay than on the op site slope off Sand Point where adjacent shallow areas of coo are more limited.

On the basis of this study, the general conclusion is drawn t a similar convective flow takes place during winter overturn on steep marginal slopes leading to the basin floor and that the f down slopes adjacent to the more extensive shallow lake marg is of greater intensity than elsewhere. Furthermore, it is sugges that these currents, upon reaching the basin floor, have ero sediment from the trough at the base of the slopes and redeposi it to form the medial ridge of the basin floor.

To obtain a qualitative understanding of the effect that s currents might have on the deposition of sediments and on the fo



ure 4. Lake-temperature structure in cross-section from Sand Point to Juanita Bay, ng intense convective flow of cold water down the marginal slopes. The temperature ı by isotherms is in degrees centigrade. See fig. 2 for location of section.

n of the W-shaped section, a series of simple model experi- ts was conducted (Fig. 6). In one of the experiments a U-shaped at-floored section similar to conditions at the end of the melt- er stage was used. Dense salty water containing blue dye to ılate cold water was introduced simultaneously into the surface er at the two sides. The resulting convection currents (Fig. 6 A–C) luced a rapid flow of water down the slopes and across the bot- to the center of the trough where the two currents collided. ıough no sediment was used in this experiment, results indicate sediments, either suspended in the water near the bottom or g in a semi-fluid recently-deposited state, would have been ied by the currents to the center of the trough and deposited e. This apparently simulates the condition that prevailed fol- ng the meltwater stage which led to the rapid build-up of the ral ridge.

ı another experiment, a W-shaped section simulating the equilib- ı profile of the present lake bottom was used (Fig. 6 D–F). se convection currents behaved similarly to those of the first experiment except in the region of the central ridge; in ascen this ridge the currents were slowed markedly, with the attenc development of large eddies which curled back over the valleys either side. Results of this experiment suggest that sediment on bottom, either in suspension or in a recently deposited state, tho disturbed and moved by the currents, would have been left i fairly even layer over the bottom, thus maintaining the equilibr W-shaped profile of the present lake floor.

In further support of the convection-current explanation certain distinctive features of the topography and sediments th selves. Among these are the thinning of sediments beneath the leys and thickening beneath the medial ridge. The fact that isola deeps within the valleys are localized adjacent to steep side slo bordering the most extensive shallow areas of the lake (Fig. 2) a further weight to the convection-current interpretation. Apparen the extensive convective flow from these areas has led to s asymmetrical profiles as the one off Union Bay (Fig. 3B) in cont to the more general symmetrical profile (Fig. 3A) where adjac embayed areas do not exist.

The mottled structure of the limnic peat, apparently produced erosion and redeposition of sediments laid down initially in ann varves, gives further evidence of the process that produced W-shaped profile. As each varve requires essentially a year to fo its destruction, if on an annual basis, could be accomplished o by seasonal currents of short duration, such as convection curre Finally, in response to the possible objection that convection rents may be too weak to erode sediment, it should be pointed that limnic peat, because of its low density and semifluid state w initially deposited, can doubtlessly be eroded and transported considerably weaker currents than those required to move m other types of sediment.

SUMMARY

In summary, the sediments and topography of Lake Washing reflect the following changes in postglacial circulation. During blue-clay phase, the circulation was apparently dominated by r flour-laden currents issuing from meltwater streams which ente the lake from the north. The U-shape or flat floor of the trough the end of this phase indicates that these cold dense currents ved the thalweg of the basin. Although convection currents were ubtlessly active during the blue-clay phase, their effect on sedi- ntation was apparently obliterated by the meltwater-induced culation. With cessation of meltwater deposition and the be- ming of predominantly organic sedimentation, convection cur- ts assumed a much more significant role. Their control on sedi- ntation and their influence in sculpturing the lake bottom is ply demonstrated by the central ridge of sediments and by the shaped configuration of the deep lake floor. Except for a 60-year rval represented by the varved layer within the limnic peat uence, convection currents associated with winter overturn have arently extended to the deepest part of the lake to erode and eposit sediments which were initially laid down as varves. Pre- mably, this varved layer records a period characterized by warm nters when surface cooling was not sufficient to bring about mplete overturn of the lake.

Although cold bottom currents originating at the shallow ends the lake (either from surface cooling in these shallow areas or m discharge of the Sammamish and Cedar Rivers) may utilize e marginal valleys to reach the deepest part of the trough, there no conceivable way in which these currents could have produced e valleys.

ACKNOWLEDGEMENTS

This investigation was supported in part by the Office of Naval search under Contract Nonr-477 (10), Project NR 083–012. A ant from the Agnes M. Anderson Research Fund of the University Washington defrayed the cost of radiocarbon analyses which re made by J. L. Kulp of Lamont Geological Observatory.

The echo-sounding traverses were run by the M.V. ONCORHYN- us, Department of Fisheries, and the cores were taken aboard e M.V. BROWN BEAR, Department of Oceanography, University of ashington. Sincere appreciation is expressed to Tom Oswald, JR., d F. W. Princehouse, masters of the vessels, and to all crew mem- rs for enthusiastic assistance in the field.

Various aspects of this investigation were discussed with J. H. ckin (Geology), W. T. Edmondson (Zoology), G. B. Rigg (Botany), A. Barnes and R. H. Fleming (Oceanography), all of the Uni- rsity of Washington; and with W. H. Bradley (U.S. Geological rvey). G. C. Anderson (Botany, University of Washington) identified the diatoms, and W. J. Clench, Museum of Comparati Zoology, Harvard University, identified the marine mollusc Acknowledgement is also due the following members of the Depar ment of Oceanography, University of Washington: Mrs. Jean Ha low and D. M. Ragan who assisted in the laboratory, and D. R. Doy and H. E. Babcock who drafted the topographic map of the la floor.

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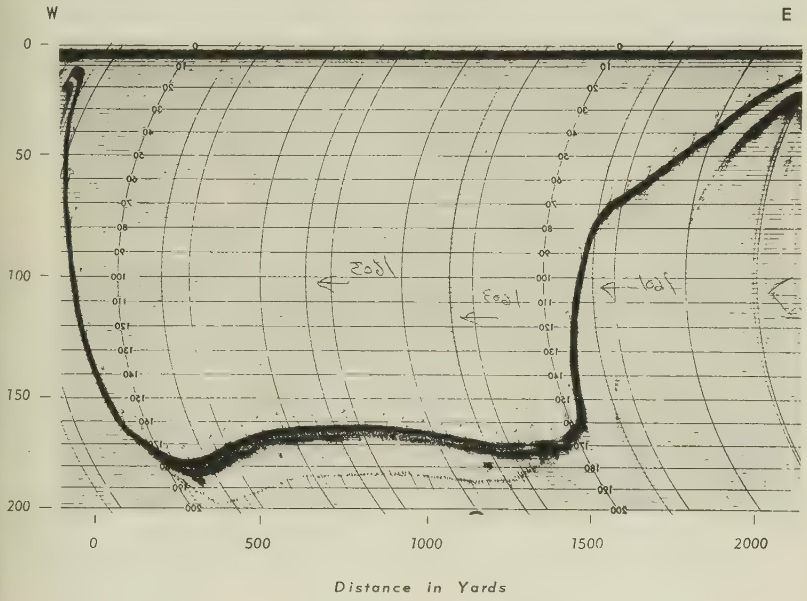

Figure 5. Echogram showing typical W-shaped configuration of the lake floor. The sub-bottom reflection about 20 feet beneath the trough comes from a 2-inch layer of volcanic ash. The record was obtained with a Bendix echo-sounder operating at a frequency of 50 kilocycles. See Fig. 2 for location of section.

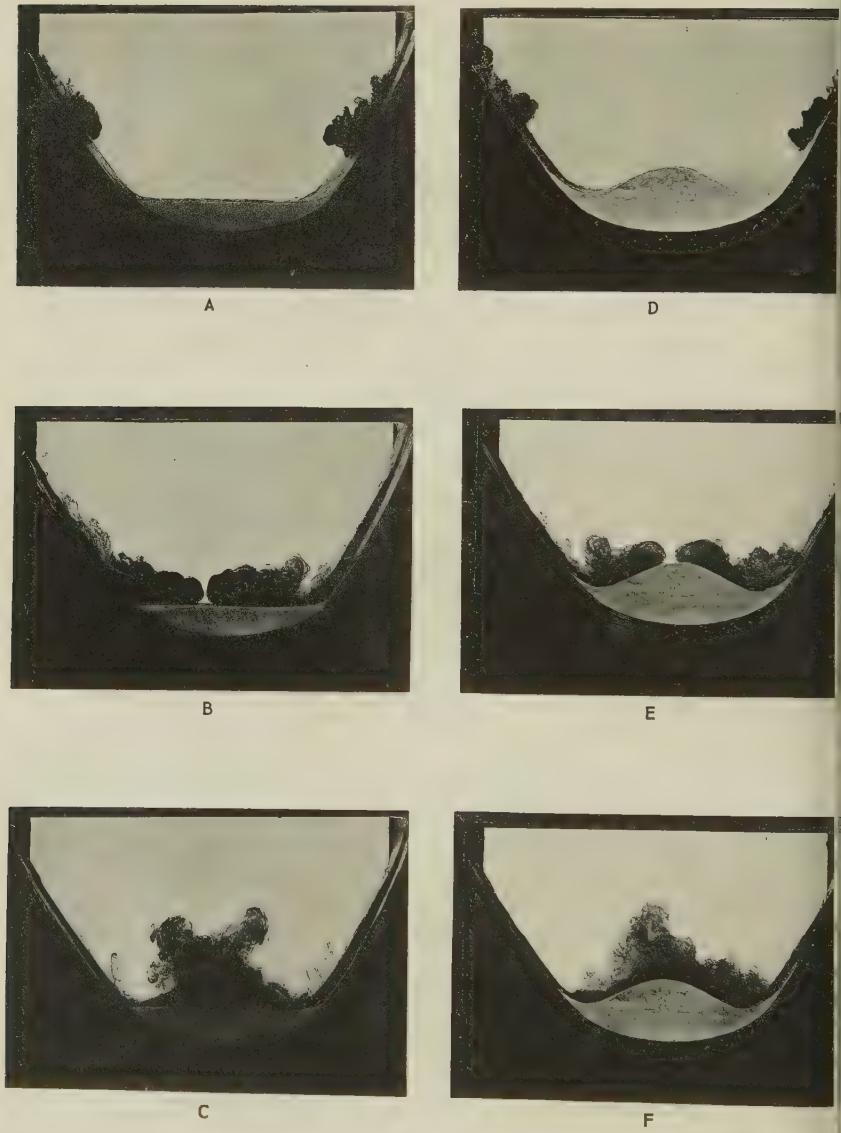

Figure 6. Convection currents produced in model experiments to simulate conditions of cor vective flow in the lake at the end of the meltwater stage (A-C) and at the present time (D-F)

A NOTE ON TIDAL FRICTION[1]

By

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ABSTRACT

he Moon's gravitational torque on the ocean tide has been computed on the of Dietrich's cotidal charts. The result is -4.5×10^{23} dynes cm as compared Heiskanen's (1921) value of -2.9×10^{23} dynes cm based on Sterneck's (1920) rts. Both values are subject to great uncertainty. The observed deceleration of Moon implies a torque of $(-3.9 \pm 1.0) \times 10^{23}$ dyne cm, which is consistent with n foregoing calculations. It is concluded that the deceleration of the Moon's ital motion and the associated deceleration of the Earth's rotation *may* be due ceanic tidal dissipation. The solar decelerating torque is estimated at 0.31 times t of the lunar torque. The forces associated with the decelerating tidal torque e rise to a minute steady oceanic circulation.

INTRODUCTION

The observed position of the Sun and Moon do not agree precisely th their ephemerides. The discrepancies are due to (1) variations the rate of rotation of the Earth and (2) variations in the orbital otion of the Moon over and above those included in the epheme- des. From simultaneous observations of the discrepancies in longi- de of the Moon and Sun (or Moon and Mercury), the two effects n be separated according to Murray's (1957) scheme. Observations nce 1680 indicate a constant deceleration[2] in the Moon's orbital otion by $11''.2$ century^{-2} (in addition to the $6''.1$ century^{-2} acceleration due to planetary perturbations allowed for in the eph erides). The modern value for the deceleration is not inconsist with discrepancies inferred from Babylonian eclipses and other cient observations (Munk and MacDonald, 1960).

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[2] If the Moon's motion is referred to a time standard based on the Earth's rotation ch as a sundial), the velocity, angular and linear, does in fact increase. If it is erred to an "absolute" time standard, the motion is decelerated. The term cular acceleration" used in astronomic literature refers to the former concept. e present discussion refers all acceleratious, etc. to absolute time.

The only theory that has been advanced to account for the an alous lunar deceleration is that it is associated with tides on Earth (Jeffreys, 1952: chap. 8). The astronomic evidence can g no information as to whether the atmosphere, the oceans or bodily tides may be responsible. Atmospheric tides are rather determined from barograms at many weather stations; however, resulting lunar[3] torque is too small by a factor of 100 to account the lunar deceleration. Bodily tides could be responsible if t lagged by 1° with respect to their equilibrium configuration (M and MacDonald, 1960), but this value is too small to be chec against measurements of Earth tides with gravimeters. Indi evidence based on the anelastic properties of the solid Earth indic that the bodily tide may be an important factor, but appare not the principal factor. This leaves the ocean tide. The observati are barely good enough to make a rough estimate possible. existence of steady tidal stresses and of a resulting westward ocea drift, first mentioned by Hertz (1883), was subsequently discus by G. H. Darwin (1898: 276). New observations conducted southern oceans during the International Geophysical Year sho lead to a substantial improvement in this estimate.

TIDAL FORCE AND TORQUE

Let ψ designate the tide-producing potential. This can be writ as a sum of three groups of terms (see, for example, Doodson, 19

$$\psi_S = -\tfrac{1}{2} B \frac{gr^2}{a} \sin^2\theta \sum_S C_i \cos(\sigma_i t + \varepsilon_i + 2\varphi)$$

$$\psi_D = -\tfrac{1}{2} B \frac{gr^2}{a} \sin 2\theta \sum_D C_i \cos(\sigma_i t + \varepsilon_i + \varphi)$$

$$\psi_L = -\tfrac{1}{2} B \frac{gr^2}{a} (\tfrac{1}{2} - \tfrac{3}{2}\cos^2\theta) \sum_L C_i \cos(\sigma_i t + \varepsilon_i),$$

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[3] This lunar atmospheric torque must not be confused with a thermally indu solar atmospheric torque that is much larger and of opposite sign.

esponding to the semidiurnal, diurnal, and long-period con- uents, respectively. Here

$$B = \frac{3}{2}\frac{M}{E}\frac{a^3}{D^3} = 0.843 \times 10^{-7}$$

dimensionless constant, M the mass of the Moon, E the mass he Earth, a the Earth's radius, D^{-1} the mean inverse distance e Moon, r the distance from the Earth centroid, θ the colatitude, east longitude, C_ι the constituent coefficients, σ_ι the frequencies, ε_ι the epochs depending on the time origin.

q. (1) includes only potentials of degree two; higher harmonics, ortional to higher powers of a/D, have been neglected. Both r or solar terms are to be included in the expansion.

he force per unit mass, $F = -\nabla\psi$, can be considered as constant n the (tidally disturbed) sea surface ($z = \eta$) to the sea bottom $-h$). The total force per unit area on a water column equals

$$\boldsymbol{\tau} = \varrho\, \boldsymbol{F}(\theta, \varphi; t)\,[\eta\,(\theta, \varphi; t) + h\,(\theta, \varphi)],$$

re ϱ is water density, assumed constant. The time-average of stress equals

$$\bar{\boldsymbol{\tau}} = \varrho\, \overline{\boldsymbol{F}\eta} \tag{3}$$

s a term $h\varrho\bar{\boldsymbol{F}}$, causing a permanent tidal deformation which is tomarily absorbed in the gravity field. The quantity $\bar{\boldsymbol{\tau}}$ as defined (3) will be referred to as the *steady tidal stress*.

trictly speaking, the time-average should be taken for each mass ticle following its tidal trajectory. Actually, we have taken time-rages in fixed columns. It turns out that the steady tidal stress istributed vertically depending on the vertical distribution of tidal current. In a frictionless homogeneous ocean the tidal rent, and hence the steady tidal forces, would be uniform from to bottom.

he tidal elevation above mean sea level can be expanded in a n similar to (1), with the components

$$\begin{aligned}
\eta_S &= \sum_S H_\iota \cos\,(\sigma_\iota t + \varepsilon_\iota + 2\varphi - \varkappa_\iota) \\
\eta_D &= \sum_D H_\iota \cos\,(\sigma_\iota t + \varepsilon_\iota + \varphi - \varkappa_\iota) \qquad (4) \\
\eta_L &= \sum_L H_\iota \cos\,(\sigma_\iota t + \varepsilon_\iota - \varkappa_\iota),
\end{aligned}$$

where H_i and $\varkappa_i$ are empirical functions of θ, φ, to be determi
from tide data. The essential feature is that the σ_i's are the sam
(1) and (4); this follows because the response of the sea surfac
the tide-producing force $\boldsymbol{F}$ contains the same frequencies as
The ε_i's are the same by appropriate definitions of $\varkappa_i$. In the
duct (3) of the summations, common frequencies have non-
means. We note that $\boldsymbol{F}$ can be precisely computed for any
graphic position according to (1); in the case of η we must dep
on interpolation between widely separated tide stations. Combi
(1), (3) and (4) we find that the steady tidal stress $\bar{\tau}$ has the c
ponents

$$\bar{\tau}_\theta = B\varrho g \left[\tfrac{1}{4}\sin 2\theta \sum_S C_i H_i \cos\varkappa_i + \tfrac{1}{2}\cos 2\theta \sum_D C_i H_i \cos\varkappa_i \right.$$

$$- \tfrac{3}{8}\sin 2\theta \sum_L C_i H_i \cos$$

$$\bar{\tau}_\varphi = B\varrho g \left[-\tfrac{1}{2}\sin\theta \sum_S C_i H_i \sin\varkappa_i - \tfrac{1}{2}\cos\theta \sum_D C_i H_i \sin\varkappa_i\right]$$

$$\bar{\tau}_r = B\varrho g \left[\tfrac{1}{2}\sin^2\theta \sum_S C_i H_i \cos\varkappa_i + \tfrac{1}{2}\sin 2\theta \sum_D C_i H_i \cos\varkappa_i \right.$$

$$+ \left(\tfrac{1}{4} - \tfrac{3}{4}\cos^2\theta\right) \sum_L C_i H_i \cos\varkappa$$

The *steady tidal torque* about the Earth's axis of rotation is

$$\bar{N} = a^3 \int_{\text{oceans}} \bar{\tau}_\varphi \sin^2\theta \, d\theta \, d\varphi .$$

In passing, let us consider the significance of the other tor
components, $\bar{L}$, $\bar{M}$. If the Earth had finite strength, these com
nents would lead to a minute permanent displacement of the
of rotation. If, on the other hand, the Earth were to yield as a fl
to prolonged stress, no matter how minute, polar wandering wo
result. Eventually the pole would reach a position (if any) for wh
$\bar{L}$ and $\bar{M}$ are zero. The trouble with this intriguing hypothesis
polar wandering is that the torques involved are small, $\bar{L}$ and
being of the same order as $\bar{N}$, 10^{23} dyne cm. The distribution
continents and oceans, if isostatically balanced, are associated w
a torque of the order of 10^{30} dyne cm (Munk and MacDon
1960: chap. 12). It should be remembered that the time-aver

taken relative to geographical co-ordinates, and hence these
ponents rotate with the Earth. If the time-average were to be
n relative to a nonrotating system, the steady torque compo-
s $\bar{L}$ and $\bar{M}$ would be fixed in space and would cause a slight
aly in the Earth's precession rate. The reader can find a dis-
on in Darwin's works (for example, see Darwin, 1898).

EVALUATION FROM COTIDAL CHARTS

e assume that the cotidal contours ($\varkappa_i$ = constant) are identical
il semidiurnal constituents and that the co-range charts differ,
from another, by a constant factor equal to the ratio of the
esponding equilibrium tides. Thus

$$\begin{aligned} \varkappa_i(\theta,\varphi) &= \varkappa_S(\theta,\varphi) \\ H_i(\theta,\varphi) &= \frac{C_i}{C_S} H_S(\theta,\varphi) \end{aligned} \qquad (7)$$

each of the semidiurnal constituents. The subscript $_S$ refers to
nportant semidiurnal constituent for which satisfactory cotidal
ts are available. Eq. (7) is essentially the "inference" method
evaluating the lesser constituents from short tide records.
ilar relations are assumed for diurnal and long-period constitu-
, but application to the long-period components is doubtful (see
ion on long-period tides). The errors inherent in the approxi-
ion (7) are smaller than those associated with existing cotidal
ts.
ith this scheme, the only summations to be performed are of
type

$$\lambda_S = \sum_S C_i^2; \qquad (8)$$

similarly for λ_D, λ_L. Eq. (5) can then be written

$$B\varrho g \left[\frac{1}{4}\frac{\lambda_S}{C_S}\sin 2\theta\,(H_S\cos\varkappa_S) + \frac{1}{2}\frac{\lambda_D}{C_D}\cos 2\theta\,(H_D\cos\varkappa_D) - \frac{3}{8}\frac{\lambda_L}{C_L}\sin 2\theta\,(H_L\cos\varkappa_L)\right]$$

$$\bar{\tau}_\varphi = B\varrho g\left[-\frac{1}{2}\frac{\lambda_S}{C_S}\sin\theta\,(H_S\sin\varkappa_S) - \frac{1}{2}\frac{\lambda_D}{C_D}\cos\theta\,(H_D\sin\varkappa_D)\right]$$

$$\bar{\tau}_r = B\varrho g\left[\frac{1}{2}\frac{\lambda_S}{C_S}\sin^2\theta\,(H_S\cos\varkappa_S) + \frac{1}{2}\frac{\lambda_D}{C_D}\sin 2\theta\,(H_D\cos\varkappa_D)\right.$$

$$+\frac{\lambda_L}{C_L}\left(\frac{1}{4}-\frac{3}{4}\cos^2\theta\right)(H_L\cos\varkappa_L$$

Values of H_S and H_D have been interpolated for every ten deg square of the oceans from Dietrich's (1944) chart of the tidal ra of the constituents M_2 and K_1, respectively. Values of $\varkappa_S$ and were read off Dietrich's cotidal charts for the same two constitue Accordingly, we take $C_S = 0.9085$ and $C_D = 0.5305$, correspond to these two constituents. The interpolated values are tabulated the Appendix. The combined lunar and solar horizontal tidal str is illustrated in Fig. 1.

THE DARWIN DEVELOPMENT

In order to use the more familiar tidal constituents from Darwi development (see for example, Shureman, 1941), we would have allow for their slowly varying amplitude over the Moon's no cycle. This is done by introducing the node factor $f_i(t)$ for ea constituent. The only modification required is that λ must be writ

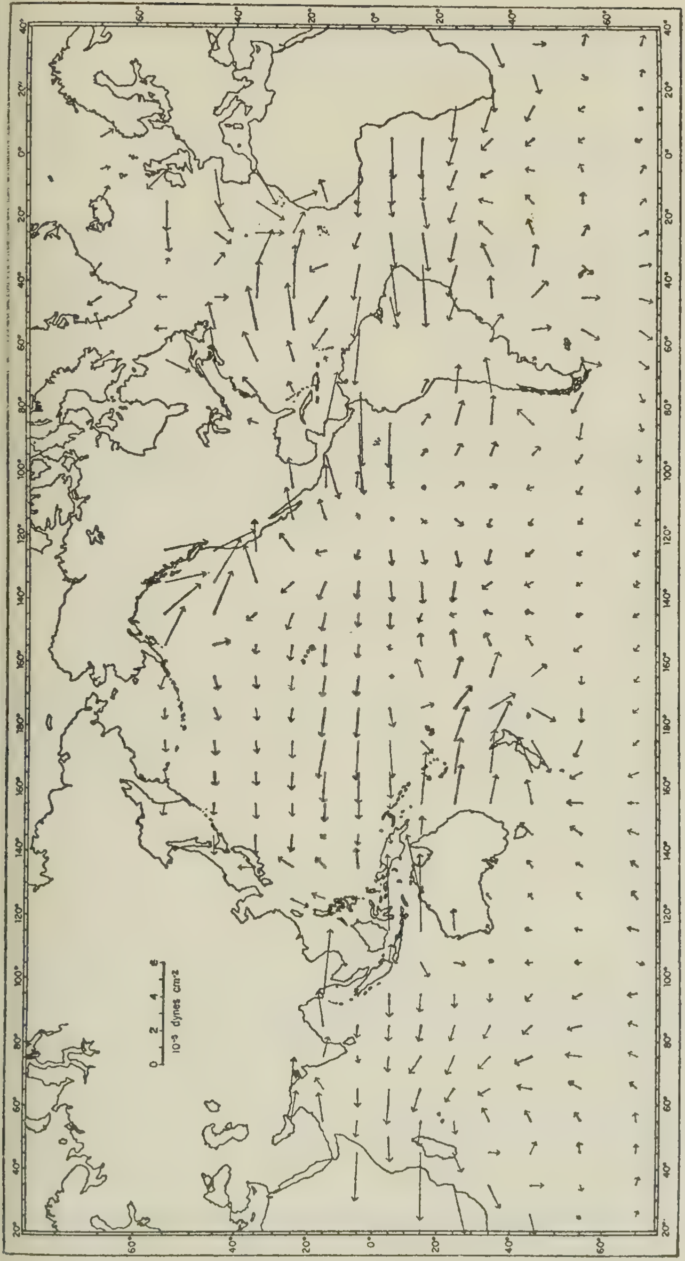
$$\lambda_S = \sum_S \overline{f_i^2}\,C_i^2; \qquad ($$

and similarly for λ_D and λ_L. The mean values of f_i^2 can be calcula by using eqs. (65) through (80), (206), (215), (227), (235), and t formula at top of page 156 in Shureman (1941). The values as follows:

Constituent	f
Mf	1.172
MSf, $2SM$, MS, M_2, N_2, $2N_2$, ν_2, λ_2, μ_2	1.0014
Ssa, Sa, P_1, S_2, R_2, T_2	1.0000[4]
K_1	1.0188
O_1, Q_1, $2Q_1$, ϱ_1, σ_1	1.0356
J_1, MP_1, SO_1, χ_1, θ_1	1.0402

---

[4] The node factors of the purely solar constituents have the constant value un



60°
40°
20°
0°
20°
40°
60°
40°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0 2 4 6
10⁻³ dynes cm⁻²

Figure 1. Horizontal component of the steady tidal stress from semidiurnal tides. The vectors are drawn from the center of each 10° square for which the stress could be computed.

Constituent	*f*
OO_1, KQ_1	1.421
M_1	2.574[5,
K_2	1.0876
L_2	1.002[5]
KJ_2	1.192

There is difficulty in separating the lunar from the solar effe with Darwin's development owing to the presence of lunisolar c stituents, especially K_1, and we shall not have further recourse to

SEPARATION OF LUNAR AND SOLAR EFFECTS

The separation of lunar and solar effects is somewhat arbitra The ambiguity arises with respect to such constituents for wh lunar and solar contributions have identical frequencies. Thus in the development, such constituents have been lumped int single term.

The principal reason for considering separately the lunar and so effects is that we may wish to evaluate the reaction of the stea tidal stress on the orbits of the Moon and Sun. In particular, anomalous secular deceleration of the Moon has been observed a attributed to tidal friction. Accordingly we define the lunar eff as the Moon's gravitational action on the *actual* tidal bulge resulti from the combined action of the Sun and Moon; similarly we c sider as the solar contribution the solar gravitational action on t combined bulge.

For the general case we need to reinterpret (8) by writing

$$\lambda_S = \sum_S C_i C_i'; \qquad ($$

and similarly for the diurnal and long-period constituents. Here is the sum of the coefficients having the frequency σ_i. This proce ure is possible because the arguments are identical for lunar a r equilibrium constituents having the same frequency. The lunar ribution to λ is given by summing (11) over the lunar constituents Thus the lunar and solar contributions are given by

---

[5] The values for L_2 and M_1 are difficult to calculate from theory and were ev uated by averaging the squares of 93 consecutive mean yearly values (approximat 5 nodal cycles), from 1850 through 1942, of the node factors given by Shuren (1941: table 14).

[6] The large value of M_1 is to be used with Darwin's miscomputed value of C(of 0.0209. (The theoretical value is 0.0317.)

$$\lambda_{S\leftmoon} = \sum_{S\leftmoon} C_{i\leftmoon}(C_{i\leftmoon} + C_{i\odot}), \quad \lambda_{S\odot} = \sum_{S\odot} C_{i\odot}(C_{i\leftmoon} + C_{i\odot}) \qquad (12)$$

ectively; and similarly for λ_D, λ_L, with the understanding that purely lunar constituents $C_{i\leftmoon} = C_i$, $C_{i\odot} = 0$, for purely solar tituents $C_{i\odot} = C_i$, $C_{i\leftmoon} = 0$, whereas for luni-solar constituents $+ C_{i\odot} = C_i$. Note that

$$\lambda_S = \lambda_{S\leftmoon} + \lambda_{S\odot} = \sum_S C_i^2, \quad \lambda_D = \ldots, \quad \lambda_L = \ldots.$$

he summations have been carried out by using Doodson's ex- sion. The results are

	λ_S	λ_D	λ_L
Lunar	**0.888**	**0.353**	**0.041**
Solar	**0.222**	**0.120**	**0.005**
Total	**1.110**	**0.473**	**0.046**
Lunar/solar	**4.00**	**2.94**	**8.2**

lunar to solar ratios are not those of the square of the equilib- n heights. These values give a rough idea of the contribution of three species to $\bar{\tau}$.

THE LONG-PERIOD TIDES

q. (7) is not a valid approximation for the long-period s. Frequencies are widely separated, and the annual and semi- ual terms are predominantly of meteorological origin[7]. Moreover seasonal tides are largely steric over most of the oceans; that the variation in sea level is associated with a change in the spe- volume of the water column. Only the variable mass per unit a contributes to $\bar{\tau}$.

n all events, the contribution from long-period tides is relatively ll. The component $\bar{\tau}_\varphi$ (and consequently $\bar{N}$) is not influenced at by long-period tides.

The meteorological contribution to the S_1- and S_2-tides has a small effect on d has been neglected.

THE STEADY TIDAL STRESS

Fig. 1 shows the horizontal component of $\bar{\tau}$ arising from se diurnal tides only. A predominance of westward stresses is appare These act in the sense required to decelerate the Earth's angu velocity. An equivalent chart for diurnal tides (not presented he has the same general appearance, but the stresses are roug one-fourth of the semidiurnal stresses. The existence of steady ti stresses and of a resulting westward oceanic drift has been discus by Darwin (1898: 276).

TABLE I. TIDAL TORQUE ON THE EARTH IN UNITS OF 10^{23} DYNE CM

	Heiskanen's Lunar Semid.	*Lunar*			*Solar*			*T*
		Semid.	*Diurnal*	*Total*	*Semid.*	*Diurnal*	*Total*	
Pacific								
+	3.5	2.7	0.0	2.7	0.7	0.0	0.7	
—	*–5.4*	*–4.0*	*–0.8*	*–4.8*	*–1.0*	*–0.3*	*–1.2*	-
Total	–1.9	–1.3	–0.8	–2.1	–0.3	–0.3	–0.5	-
Atlantic								
+	1.7	1.6	0.1	1.7	0.3	0.0	0.3	
—	*–2.5*	*–3.0*	*–0.1*	*–3.1*	*–0.7*	*0.0*	*–0.7*	-
Total	–0.8	–1.4	0.0	–1.4	–0.4	0.0	–0.4	-
Indian								
+	2.3	1.3	0.1	1.4	0.3	0.0	0.3	
—	*–2.5*	*–2.1*	*–0.3*	*–2.4*	*–0.6*	*–0.1*	*–0.7*	-
Total	–0.2	–0.8	–0.2	–1.0	–0.3	–0.1	–0.4	-
Grand Total	–2.9	–3.5	–1.0	–4.5	–1.0	–0.4	–1.3	-

The irrotational component of the stress field would result in steady distortion of the sea surface relative to the geoid by t order 10^{-4} cm. There is no associated circulation. The rotatio component of the stress field causes a steady circulation and surfa displacement. We might make an estimate by analogy to the stea wind-driven circulation. Typical wind stresses are of the order several dynes cm^{-2}, or 10^5 times the steady tidal stresses. In t western boundary zone, where the currents are strongest, the c served transport per unit width is of the order 10^7 cm^2 sec^{-1} a is concentrated near the surface. The maximum surface displa t is about 10^2 cm. Accordingly, we might expect the steady l transport and the surface displacement to be 10^2 cm^2 sec^{-1} and cm, respectively. If the velocity is distributed uniformly from to bottom, its maximum might attain 10^{-3} cm sec^{-1}. This is gether negligible. Observed steady deep currents in the western dary zone are of the order of one cm sec^{-1} (Swallow and Worgton, 1957). Away from the western boundary zone, the steady nts are probably an order of magnitude less.

this calculation we have not allowed for distortion of the sea om. Such a distortion arises directly from the tide-generating as well as from the variable load of the ocean tide. The load ection would be difficult to apply, if at all possible; one would to evaluate the contribution of the ocean tide to the spherical ace harmonic of second degree (as a function of time), and y the appropriate Love numbers (Munk and MacDonald, 1960). elated geophysical problems such corrections have been of the er of 20 to 30 %.

THE STEADY TIDAL TORQUE

able I summarizes the torque calculation. Integration (6) was ied out separately for the Sun and Moon, for semidiurnal and rnal tides, and for the three major oceans. For each of these 12 ulations the positive and negative contributions to the torque gral were evaluated separately, as shown. In general the positive negative contributions are of the same order, which implies a siderable uncertainty in the sum. It is encouraging that in each he 12 instances the sum is negative or zero.

ur results for the lunar semidiurnal tide agree well with Heisen's (1921) calculation. He neglected the lunar diurnal effect, ich we find to be only one fourth of the total lunar effect. The bined lunar torque of $-4.5 \times 10^{+23}$ dyne cm is to be compared h the value $-3.9 \times 10^{+23}$ inferred from the astronomically observed eleration of the Moon. The agreement is better than we have right to expect. The chief uncertainty has to do with the poorly wn tidal amplitudes in the open sea.

n a similar manner, solar torque must be associated with a eleration of the Sun's motion around the Earth, but because of large mass and distance of the Sun, this effect is far too small be observed.

APPENDIX. VALUES OF H AND κ, DEDUCED FROM DIETRICH'S CATIDAL CHARTS, WH
SQUARE INDICATED BY CO-ORDINATES OF ITS MIDPOINT. THE FOUR VA

	5E	15E	25E	35E	45E	55E	65E	75E	85E	95E	105E	115E	125E	135E
75N	35	30	40	—	—	—	—	—	—	—	—	—	—	—
	010	030	050	—	—	—	—	—	—	—	—	—	—	—
	05	06	06	—	—	—	—	—	—	—	—	—	—	—
	155	195	205	—	—	—	—	—	—	—	—	—	—	—
65N	40	—	—	—	—	—	—	—	—	—	—	—	—	—
	330	—	—	—	—	—	—	—	—	—	—	—	—	—
	10	—	—	—	—	—	—	—	—	—	—	—	—	—
	175	—	—	—	—	—	—	—	—	—	—	—	—	—
55N	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
45N	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
35N	—	—	—	—	—	—	—	—	—	—	—	—	—	50
	—	—	—	—	—	—	—	—	—	—	—	—	—	180
	—	—	—	—	—	—	—	—	—	—	—	—	—	22
	—	—	—	—	—	—	—	—	—	—	—	—	—	185
25N	—	—	—	—	—	40	40	—	—	—	—	50	50	40
	—	—	—	—	—	290	280	—	—	—	—	170	190	195
	—	—	—	—	—	45	45	—	—	—	—	20	20	18
	—	—	—	—	—	055	065	—	—	—	—	205	215	205
15N	—	—	—	—	40	40	35	30	45	80	—	—	50	40
	—	—	—	—	210	235	200	310	245	290	—	—	185	195
	—	—	—	—	35	39	35	30	12	11	—	—	15	15
	—	—	—	—	045	055	065	045	355	005	—	—	215	210
05N	55	—	—	—	60	35	20	20	20	30	—	—	50	40
	110	—	—	—	115	120	070	015	140	190	—	—	180	210
	10	—	—	—	28	28	20	10	08	08	—	—	15	15
	005	—	—	—	045	055	055	045	325	305	—	—	215	215
05S	45	45	—	—	80	50	45	25	20	25	40	75	—	—
	095	105	—	—	110	115	060	040	070	105	210	290	—	—
	10	08	—	—	18	20	10	02	04	10	20	20	—	—
	025	040	—	—	045	055	085	075	250	245	245	255	—	—

tions. The Values Represent a Sort of Subjective Average over the Ten Degree
ranged in the Following Order: H, k for M_2; H, k for K_1

155W	145W	135W	125W	115W	105W	95W	85W	75W	65W	55W	45W	35W	25W	15W	5W
—	—	—	—	—	—	—	65	45	45	45	—	–	40	40	40
–	—	—	—	—	—	—	280	300	310	315	—	—	310	000	090
—	—	—	—	—	—	—	35	35	35	35	—	—	05	05	05
-	—	—	—	—	—	—	155	165	160	155	—	—	095	105	115
—	—	—	—	—	—	—	—	—	45	45	40	40	40	40	25
–	—	—	—	—	—	—	—	—	330	250	150	130	190	060	350
—	—	—	—	—	—	—	—	—	25	25	10	10	07	05	07
—	—	—	—	—	—	—	—	—	125	125	105	095	090	100	115
0	100	100	100	—	—	—	—	–	60	30	20	10	35	55	60
300	325	350	350	—	—	—	—	—	020	180	180	290	080	090	140
40	40	40	40	—	—	—	—	—	15	15	08	05	04	10	10
115	110	110	115	—	—	—	—	—	115	115	100	085	080	080	115
35	80	90	100	—	—	—	—	60	55	45	25	25	40	60	60
350	300	310	340	—	—	—	—	230	260	250	000	320	025	050	080
36	36	37	35	—	—	—	–	06	07	07	05	04	05	07	07
085	090	100	115	—	—	—	—	105	115	110	090	070	055	055	065
10	25	60	40	40	—	—	20	40	50	60	50	60	65	70	60
105	160	240	265	270	—	—	190	210	230	250	275	310	000	020	050
26	29	31	32	31	—	—	07	05	05	05	03	04	05	06	06
080	085	090	095	095	—	—	125	120	120	125	105	040	030	030	050
20	25	35	40	45	40	—	—	20	30	60	65	50	40	65	—
110	130	160	210	240	250	—	—	215	230	250	275	300	320	350	—
16	18	20	18	18	17	10	10	09	07	05	04	04	06	06	—
080	080	085	085	080	065	290	275	135	145	170	205	305	345	000	—
25	25	35	40	35	25	80	80	—	05	65	85	75	40	40	—
115	130	150	175	220	270	040	310	—	230	160	160	175	190	220	—
10	10	11	13	15	16	16	10	10	10	05	04	04	05	05	—
080	080	085	075	055	045	015	005	180	165	190	215	275	315	345	—
15	15	25	30	20	20	75	85	85	—	80	90	90	65	60	55
130	115	135	165	195	300	035	065	100	—	130	150	155	165	180	110
05	05	06	08	10	12	13	13	13	—	05	08	05	05	10	12
085	075	075	035	015	355	340	335	345	—	215	225	265	305	335	355
05	15	25	25	20	10	35	50	—	—	—	100	90	60	35	40
050	085	125	150	180	180	095	085	—	—	—	160	140	140	155	105
02	02	04	05	07	08	09	11	—	—	—	08	05	05	07	10
235	275	315	315	305	315	325	320	—	—	—	225	265	290	330	355

	5E	15E	25E	35E	45E	55E	65E	75E	85E	95E	105E	115E	125E	135E
15S	45	45	—	80	80	30	45	30	20	20	35	90	100	—
	085	095	—	115	090	070	035	040	060	095	150	275	310	—
	06	06	—	05	12	10	07	05	05	10	18	22	22	—
	055	060	—	035	055	085	155	205	230	245	255	265	305	—
25S	40	45	—	70	35	15	30	30	20	15	15	25	—	—
	055	070	—	120	140	110	030	045	060	090	170	280	—	—
	05	05	—	03	05	04	04	04	05	09	17	20	—	—
	095	090	—	275	135	155	195	210	145	245	255	280	—	—
35S	30	40	50	40	25	20	25	30	20	10	05	10	10	15
	030	060	095	130	180	320	015	030	050	075	210	310	320	330
	04	05	05	05	04	03	04	04	06	10	15	17	19	20
	125	135	175	175	180	190	205	220	240	260	295	315	350	015
45S	20	25	30	25	20	20	30	40	20	15	10	10	10	15
	025	055	110	180	240	305	350	015	035	040	360	350	310	315
	05	04	04	04	04	04	04	05	08	12	17	20	20	20
	115	135	155	170	200	235	255	275	295	305	320	330	345	005
55S	10	05	10	20	20	20	30	35	30	20	15	15	15	15
	025	055	110	250	280	310	335	355	010	020	360	350	310	320
	07	06	05	04	04	04	05	07	10	14	20	22	25	26
	080	075	025	260	295	315	320	330	330	335	335	345	355	005
65S	15	15	15	20	20	20	25	25	25	20	20	20	20	20
	240	230	245	260	270	280	315	340	350	010	165	350	315	325
	08	07	06	04	05	05	07	10	13	16	20	23	25	28
	035	015	005	345	335	345	350	355	360	005	360	355	360	005
75S	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—

155W	145W	135W	125W	115W	105W	95W	85W	75W	65W	55W	45W	35W	25W	15W	5W
15	15	25	20	10	10	20	30	30	—	—	—	75	50	35	35
290	035	100	135	160	180	200	200	210	—	—	—	105	120	125	090
04	03	04	05	06	07	09	10	14	—	—	—	04	03	02	05
265	275	285	295	305	315	305	310	315	—	—	—	195	185	120	065
20	15	25	20	20	20	20	35	35	—	—	35	45	40	30	30
290	010	070	120	160	195	220	235	255	—	—	050	060	060	050	050
03	03	03	04	07	08	10	11	11	—	—	06	05	04	04	04
275	280	285	295	305	315	320	325	325	—	—	130	135	130	125	120
20	15	20	20	10	10	20	40	50	—	30	30	40	35	30	25
305	355	025	065	120	190	240	265	285	—	220	275	310	330	350	015
04	04	05	05	08	12	12	13	13	—	03	04	04	04	05	05
280	285	295	300	305	315	325	325	335	—	115	105	100	105	105	115
20	15	15	15	10	10	20	40	40	05	40	40	35	25	20	15
310	350	020	035	055	015	220	325	340	230	185	220	260	295	325	355
05	05	07	08	12	15	16	16	15	10	05	05	04	05	05	06
290	295	300	310	315	320	335	340	350	295	050	065	075	080	090	100
15	10	10	10	10	15	20	40	45	45	45	40	25	20	20	15
040	010	025	040	050	060	050	050	060	170	155	180	145	240	270	300
09	11	12	14	17	18	19	20	20	18	12	08	05	06	06	07
295	300	310	315	320	335	345	000	015	025	035	045	055	065	065	075
15	15	15	15	15	15	20	20	25	30	40	35	30	25	20	20
050	035	040	045	060	075	090	105	120	140	145	165	190	205	225	240
17	18	19	21	24	26	27	28	30	30	15	12	10	09	08	08
315	320	320	325	335	345	350	000	005	000	000	005	015	025	030	035
10	10	10	10	10	10	10	15	—	—	30	20	25	20	20	—
050	050	050	060	070	085	095	115	—	—	140	155	175	195	210	—
20	20	22	24	26	28	30	30	—	—	15	14	12	10	09	—
355	350	345	350	355	000	005	010	—	—	355	000	005	010	015	—

Both lunar and solar torques contribute appreciably to the celeration of the Earth's rotation. The total value is

$$\frac{\bar{N}}{I} = \frac{-5.8\times 10^{23}}{.81\times 10^{45}} = -7.1\times 10^{-22}\ \ \text{rad}\ \ \ \text{sec}^{-2},$$

where I is the Earth's principal moment of inertia. This is of same order as the observed deceleration since Egyptian times. exact comparison is impossible because of much larger eff arising from variations in the Earth's moment of inertia.

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INTERTIDAL BARNACLES OF BERMUDA[1]

By

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arnacles collected at seven localities in Bermuda by T. A. and Stephenson while conducting an ecological survey of the inter- fauna and flora were sent to the author for identification. The ection is of interest since little is known of the barnacles of e islands. Verrill (1901) described a new variety of *Balanus* *vis* Darwin from a sponge and briefly described and figured ing specimens of *Catophragmus imbricatus* Sowerby; he also stated t *Tetraclita squamosa* (Bruguière) was the commonest intertidal nacle, but he did not describe or figure this species. Specimens *B. declivis* from Bermuda examined by Pilsbry (1916) agreed h Darwin's original description (1854) of specimens from the st Indies. Pilsbry therefore concluded that Verrill's variety is not id but that the denticles found on the rostrum of Verrill's specens were produced by breakage or erosion. Crozier (1916) reted the occurrence of two specimens of *Conchoderma virgatum* engler) on a fish, *Diodon hystrix*.

he species in the present collection are *Catophragmus imbricatus* werby; a new subspecies of *Chthamalus stellatus* (Poli); *Balanus* *phitrite hawaiiensis* Broch; and *Tetraclita squamosa stalactifera* marck). Numerous specimens of *C. imbricatus* in all stages of velopment were collected under an overhanging cliff on an isoed offshore island. This find is of special interest since only young incomplete specimens of *C. imbricatus* have been found previsly; furthermore, the genus *Catophragmus*, which contains only other species, is the most primitive genus in the Recent Balanorpha. The original description by Darwin (1854) was based on specimens from the West Indies, one young (5 mm in diameter), other mature but lacking opercular valves, supplementary plates,

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the basis, and the animal. Verrill's specimens from Bermuda w 5 to 8 mm in diameter. Broch (1922) described a new species *Catophragmus* from Panama, based on several large broken sp mens lacking the basis. However, comparison of his description w the mature specimens from Bermuda indicates that his specie synonymous with *C. imbricatus*.

The new subspecies of *Ch. stellatus*, found at all seven locali sampled, is, according to the Stephensons (1954), the most commo found barnacle in the intertidal region. *T. squamosa stalactif* contrary to Verrill's findings, was found at only one locality all the specimens were small. It would be interesting to kr whether this species has been superseded by *Ch. stellatus* or whet the scarcity was due to recent adverse conditions. *B. amphit hawaiiensis*, which is a common fouling barnacle with a wide tribution, was found in two harbors.

Genus *Catophragmus* Sowerby

Catophragmus Sowerby, 1827: plate; Darwin, 1854: 485; not Pilsbry, 1907: in part, 1916: 334.

Not *Catophragmus* (*Chionelasmus*) Pilsbry 1911: 82; 1916: 335.

Diagnosis: Interior compartments eight; alae on both sides rostrum and carina and on rostral sides of laterals and carinolater radii not differentiated; several exterior whorls of supplement plates. Basis calcareous or membranous. Caudal appendages pres or lacking. Intertidal.

Remarks: Pilsbry (1916) instituted two subgenera: *Catophragm* s. str., and *Catomerus* for the two species in this genus. The first s genus is characterized by a calcareous basis and caudal appenda the latter by a membranous basis and no caudal appendages. also included the subgenus *Chionelasmus* Pilsbry (1911), contain one deep water species which he described in 1907. The specime which were broken, had one whorl of supplementary plates, a caudal appendages; there were only six compartments, and he sumed that the laterals were lacking. However, Nilsson-Can (1928) raised *Chionelasmus* to generic rank after he found a w preserved specimen with only six compartments (carinolater lacking). In a discussion of the phylogeny of *Chionelasmus*, Nilss Cantell concluded that it is derived from a *Catophragmus*-like fo by the side of that genus and that it is not an intermediate fo ween *Catophragmus* and genera such as *Chthamalus*, which have compartments but which lack supplementary valves. He stresses difference in structure of the supplementary plates in the two ra but, as will be seen in the description of *C. imbricatus*, no great difference exists. On the basis of the number of compart- ts and rows of supplementary plates, *Catophragmus* is the most itive Balanomorpha.

Catophragmus imbricatus Sowerby

Plates 1, *a–g*; 2, *a–j*; 3, *a–g*; 4, *a–d*; 6, *a–e*

ragmus imbricatus Sowerby, 1827: plate; Darwin, 1854: 490; Verrill, 1901: l. 8, figs. 8, 9. *Catophragmus Pilsbryi* Broch, 1922: 298, figs. 45 a–d, 46 a–d.

ocality: Gurnet Rock, with *Chthamalus stellatus thompsoni* and *aclita squamosa stalactifera* (numerous specimens, USNM 195758).

escription: Shell conical, slightly depressed, usually corroded on osed parts of primary compartments in adults; white. Inside of partments smooth, below weakly ridged sheath; lateral edges ompartments with alae projecting inward in lower part. Orifice mboidal, slightly toothed in young and noncorroded specimens. cimens 3 to 4 mm in diameter, usually with only one row of plementary plates, covering sutures of primary compartments extending to basis. Slightly larger specimens than these with or two additional whorls of plates. Specimens 8 to 15 mm in meter with five or six whorls of supplementary plates (Pl. 1, *a* and Number of rows usually varying somewhat on different compart- nts; in extreme cases, some compartments with six whorls, ers with only one or two. On extensively corroded specimens, plementary plates thin or not distinguishable.

xposed surface of primary compartments ribbed in young but ally corroded in adults. Surface under supplementary plates kly ribbed even in corroded specimens. Compartments denticulate base. Rostrum and carina (Pl. 3, *a–b* and *f–g*) larger than other es; carina usually somewhat larger than rostrum. Both plates e an arched central part and lateral alae scarcely differentiated n rest of valve except for lack of ridges. Laterals larger than inolaterals; alae of both (Pl. 3, *d–e*) with beveled edges fitting inst internal ridges of rostrolaterals and laterals, respectively. ernally, laterals and carinolaterals (Pl. 2, *b–c*) hollowed out on carinal sides, which fit over alae of adjacent compartments. R trolaterals (Pl. 3, *c*), except for median ridge and part immediat below it, overlapping alae of rostrum and laterals; radii not dif entiated. Internally, rostrolaterals (Pl. 2, *a*) with a prominent c tral ridge extending nearly to base; externally, in corroded sp mens, ridge usually visible at apex of valve.

External surface of supplementary plates ribbed in young a noncorroded specimens (Pl. 1, *b*). Plates varying greatly in b size and shape; largest plates generally covering sutures of prim plates, in some specimens being equal to or even exceeding rost laterals in size, usually decreasing in size toward base. Lar plates in most older specimens subtriangular, in young and n corroded forms with pointed apices (Pl. 1, *b*). Supplementary pla extending to basis denticulate at base (Pl. 2, *f–i*). Plates cover sutures of primary compartments or overlapping both adjoin supplementary plates with internal ridges (Pl. 2, *d*, *h*) like those rostrolaterals. Plates overlapping only one adjoining plate resem laterals and carinolaterals internally (Pl. 2, *e*, *f*, *i*, *j*) except that s corresponding to radii may occur on either side depending on wh side overlapping occurs. A few plates not overlapping either or b adjoining plates. In case of no overlapping, beveled edge fits agai beveled edge of adjoining plate (Pl. 2, *g*).

Calcareous basis rather thin in middle part but usually rema ably thick near periphery, often lengthened, at least in part. D ticles on inside similar to those at bases of compartments and s plementary plates. In spreading forms, several whorls of sup mentary plates may be attached to basis peripheral to prim compartments.

Diameter: carinorostral 15 mm, lateral 13 mm; greatest hei 6 mm. Diameter: carinorostral 13 mm, lateral 15 mm; great height 7 mm. Diameter: carinorostral 4 mm, lateral 5 mm; heig rostrum 2 mm, carina less than 1 mm.

Opercular valves often asymmetrical (Pl. 4, *a–d*), especially corroded specimens. Scutum (Pl. 1, *e*) in young with external sul in middle of valve, extending from apex to basal margin. Grow ridges moderate in noncorroded specimens. Internally (Pl. 4, *a*- articular furrow deep both above and below prominent articu ridge. In noncorroded specimens (Pl. 1, *f*), upper furrow not stron developed. Adductor ridge absent and adductor scar scarcely cernible; small pit for depressor muscle. Externally, terga (Pl. 1, moderate growth ridges in noncorroded specimens; crests for essors project below basal margin; spur not differentiated. Inally (Pl. 1, *g*; Pl. 4, *c–d*), articular ridge strong and articular ow deep and wide. Crests for depressor muscle thin and short, pying at least half of basal margin.

brum bullate, with row of small blunt teeth and hair on mar-Palps (Pl. 6, *b*) not meeting in middle; ends rounded. Mandible 6, *d*) with three teeth, about equal in size; pectinate lower edge one larger spine near inferior angle; upper margins of second third teeth usually pectinate. First maxilla (Pl. 6, *c*) with deep r notch, weaker lower notch and spines in three groups: one pair and about six small spines above upper notch; about 20 um-sized spines in broad middle section; and about 10 fine es on the protuberant lower margin. Second maxilla (Pl. 6, *a*) notch lacking spines. First two cirri subequal; many of spines inate, those on terminal segments not larger than other spines. erior cirri with four pairs of spines and occasionally a minute pair, a few small, single spines between paired spines, about short spines on distal angle, and fine multifid spinules on distal ires. Caudal appendages of mature specimens (Pl. 6, *e*) with six nents increasing in width proximally; spines on distal sutures it the same length as terminal spines. Caudal appendages of a imen 5 mm in diameter with only three segments.

emarks: Young specimens agree with Darwin's description in ing caudal appendages with only three segments and in having er similar characters as well. Mature specimens agree with the ies described by Broch (1922) in having six segments in the dal appendages and a large number of supplementary plates, two characters which he used to differentiate his species from *mbricatus*. As there are only minor differences between Broch's imens and the Bermuda specimens, the young of which agree Darwin's description, Broch's species is considered not valid. ch's specimens were all large, the largest being at least 55 mm liameter. It would be interesting to know if *C. imbricatus* ever hes this size in Bermuda or the West Indies. Darwin's large imen (18 mm in diameter) was only a little larger than the est in the lot from Bermuda.

Genus *Chthamalus* Ranzani

Chthamalus Pilsbry, 1916: 293 (synonymy).

Chthamalus stellatus thompsoni, new subspecies[2]

Plates 7, *a–e*; 8, *a–h*; 9, *a–d*

Type: Holotype, USNM 102571 (type locality, St. BRH-17: Harrington Sc Bermuda).

Localities: Cobbler's Island; Castle Island; Harrington Sou Pillars at entry to the Reach, with *Balanus hawaiiensis*; N Rock; Gurnet Rock, with *Tetraclita squamosa stalactifera* and *C* *phragmus imbricatus*; St. George's Harbor, Smith's Island, *Balanus amphritrite hawaiiensis* (numerous specimens, US 195758).

Diagnosis: *Ch. stellatus thompsoni* differs from other subspecie *Ch. stellatus* by a combination of the following characteristics: s thin, easily broken apart; radii differentiated in noncorroded sp mens; epidermis persistent; teeth present on first cirrus; and t of spination of first and second cirri.

Description: Shell (Pl. 8, *f–h*) conical, sometimes depressed, usu corroded in adults; orifice small to moderate. In young or n corroded specimens, wall thin, smooth or ribbed, sometimes w epidermis at base (Pl. 9, *a*); compartments easily separated; ra usually differentiated, with oblique summits; alae with obli summits. In corroded specimens radii, and sometimes sutures, differentiated. Color, in young or noncorroded specimens, whit white with purple or with Prussian red splotches; in corro specimens, white or dirty white. Sheath short, purple or pruss red; inner lamina immediately below sheath usually Prussian the rest dull purple.

Carinorostral diameter of largest specimen, 14 mm; height 6 m Carinorostral diameter of largest specimen with radii differentia 7 mm; height 4 mm.

Opercular valves relatively small, often asymmetrical (Pl. 8, *a* Scutum, externally (Pl. 9, *c*), white with fine growth ridges and

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[2] It is a pleasure to name this subspecies after Dr. Thomas G. Thompson tiring Professor of Oceanography, University of Washington, in recognition o outstanding contributions to oceanography.

tudinal striations in well-preserved specimens; internally
8, *a*, *b*, *d*), uniformly white or buff-colored or splotched with
le, often deeper in color on articular ridge and in a band parallel
ccludent margin. Articular ridge moderately strong, length a
more than half the tergal margin; in noncorroded specimens
ing slightly toward apex, end rounded; in corroded specimens
nearly straight, end truncate. Pit for adductor muscle deep,
cted at lower end with a narrow shallow furrow running to
of valve close to occludent margin; usually a similar furrow
upper end of pit to apex; tergal margin of pit often raised,
ng an adductor ridge; surface above pit roughened in older
iduals. Pit for depressor muscle small but usually deep, oc-
nally crossed by one or two ridges.

rgum (Pl. 8, *c*, *e*) narrow and thick; spur short with a bluntly
ed or obliquely truncate end; externally (Pl. 9, *b*), white; intern-
uniformly white, buff-colored, or splotched with purple, often
er in color on articular ridge; in large specimens, concave with
w of small pits parallel to scutal margin in lower part of con-
y; articular ridge reflexed over a wide articular furrow; crests
inent.

brum (Pl. 9, *d*) with teeth and spines along entire edge. Palp
7, *b*) narrow with rounded end; short pectinated spines on
, long pectinated spines on end. Mandible (Pl. 7, *d*) with four
and fine spines on lower third of anterior margin; fourth tooth
, second and third teeth usually with extra teeth. First maxilla
7, *a*) with two large spines above notch, three or four small
es in notch, a group of about seven intermediate-sized spines
iddle third of the edge, followed by eight or nine finer spines
slight prominence; upper and lower margins spinose. Second
lla (Pl. 7, *c*) with a deep notch lacking spines; lower lobe nearly
times larger than upper.

e armature of the first two cirri differs considerably from that
her subspecies of *Ch. stellatus*. First cirrus with subequal rami
ven and six segments; anterior ramus (Fig. 1) with conic teeth
osterior borders of the three basal segments, one or two spines
a few multifid spinules on posterior distal angles, and pectinate
es among the long spines on terminal segment and on some of
other segments. Teeth on basal segment arranged in either a
e row of about six on posterior margin or in two or three par-
rows of about six teeth each; on adjacent segments, one to

five teeth on posterior borders; rarely, teeth on the basal segr
are replaced by a single row of spines. Posterior ramus with si
ten wide doubly-serrate spines on terminal segment, pectinat
plumose spines among long spines on other segments, and
multifid spinules on distal sutures near posterior margin. Pe
with plumose spines on posterior margin. Second cirrus with
of six or seven segments; anterior ramus two segments longer
posterior one. Both rami with six to twelve thick doubly-ser

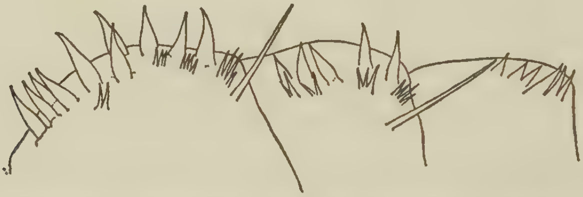

Figure 1. *Catophragmus imbricatus* Sowerby. Basal segments of anterior ramus o
cirrus. Peter McCrery.

spines (Pl. 7, *e*) on terminal segments and usually with severa
one or two adjacent segments; pectinate spines among long sp
on other segments; and fine multifid spinules on distal sutu
Anterior ramus usually with fine flat spines on posterior borde
basal segment. Pedicel with fine plumose spines at posterior d
angles and along anterior margins of both segments. Posterior
with five pairs of spines and fine multifid spinules on distal sutu
posterior borders of basal segments of rami and of pedicel
short fine spines. Rami of third cirrus with 18 segments, fo
cirrus with 20 and 19, fifth cirrus with 18, and sixth cirrus
20 and 18. Penis sparsely hairy with a terminal tuft of hairs

Remarks: Some corroded specimens of *Ch. s. thompsoni* migh
difficult to distinguish from *Ch. s. angustitergum* Pilsbry with
examining the animal. In young and noncorroded specimens t
two subspecies are easily differentiated by the presence of radii
epidermis, by the raised tergal edge of the pit for the addu
muscle, by the shape of the articular ridge of the scutum, an
the shape of the spur in *Ch. s. thompsoni*. *Ch. s. thompsoni* ma
distinguished from *Ch. fragilis* Darwin by narrower terga. The
ence of teeth on the basal segments of the first cirrus and the
tribution of the thick pectinated spines on the first and se

are the most reliable criteria for differentiating *Ch. s. thompsoni* n both *Ch. s. angustitergum* and *Ch. fragilis*. The teeth on the l segments of the first cirrus are similar to those found on the l segments of the first two cirri in *Ch. cirratus* Darwin and of first cirrus of *Ch. challengeri* Hoek, but *Ch. s. thompsoni* differs tly from these species in other characters.

Genus *Balanus* da Costa

nus Pilsbry, 1916: 49 (synonymy).

Balanus amphitrite hawaiiensis Broch

Plates 5, *c–e*; 9, *e–g*.

nus amphitrite hawaiiensis Broch, 1922: 314, figs. 56, 57 a–e.

ocalities: Pillars at entry to Reach, with *Chthamalus stellatus npsoni* (6 specimens); St George's Harbor, Smith's Island, with *hamalus stellatus thompsoni* (7 specimens); USNM 195758.

emarks: The specimens agree well with specimens from the west st of Florida and Beaufort, North Carolina which were previously ntified as *B. amphitrite denticulata* Broch (Henry, 1959). However, mination of a large series of *B. a. hawaiiensis* from the Hawaiian Philippine Islands, Japan, and China led to the conclusion that se two subspecies cannot be differentiated. Uchinomi (1956) in- ated that he believes *B. a. denticulata* is synonymous with *B. a. vaiiensis*.

ost of the specimens are corroded (Pl. 5, *d*), with splotches of nder on one or two compartments. The radii are wide, with mits parallel to the basis. The opercular valves (Pl. 5, *c*, *e*; 9, *e*, *g*) white splotched with purple externally and internally. There is it below the adductor ridge of the scutum but no intermediate ge. The spur of the tergum is over one-third the width of the al margin; the end is pointed in young forms and truncate in ture specimens. The largest specimen has a carinorostral diameter 21 mm and a height of 12 mm.

he labrum (Pl. 9, *f*) has numerous teeth extending into the notch all specimens examined. The mandible has five teeth; the fifth th is not confluent with the inferior angle. In the larger specimens anterior ramus of the fourth cirrus has teeth on the anterior

margin like those on both rami of the third cirrus. The poste
cirri have five pairs of spines.

Genus *Tetraclita* Schumacher

Tetraclita Pilsbry, 1916: 248 (synonymy).

Tetraclita squamosa stalactifera (Lamarck)

Plates 2, *a*; 5, *a–b*

Balanus stalactiferus Lamarck, 1818: pl. 4, figs. 6, 7.
Tetraclita squamosa stalactifera Pilsbry 1916: 254 (synonymy).

Locality: Gurnet Rock, with *Chthamalus stellatus thompsoni*
Catophragmus imbricatus (about 50 specimens, USNM 195758).

Remarks: Most of the specimens are 4 mm or less in carinoros
diameters; the three largest have carinorostral diameters of 8
and 5 mm. The shell is conical, faintly ribbed, with a small orif
radii are not differentiated. There is a single row of longitudi
tubes in all except the largest specimen, which has a few second
tubes in the rostrum. The shell and the opercular valves are wh

The scutum (Pl. 5, *a*) differs somewhat from that of mat
specimens. The adductor ridge is short and close to the artic
ridge; the narrow and shallow furrow between the adductor
articular ridges extends to the apex of the valve. There are six
seven oblique teeth on the inflected scutal margin. The terg
(Pl. 5, *b*) is rather narrow, not beaked; the spur is united with
basiscutal margin and has a rounded end.

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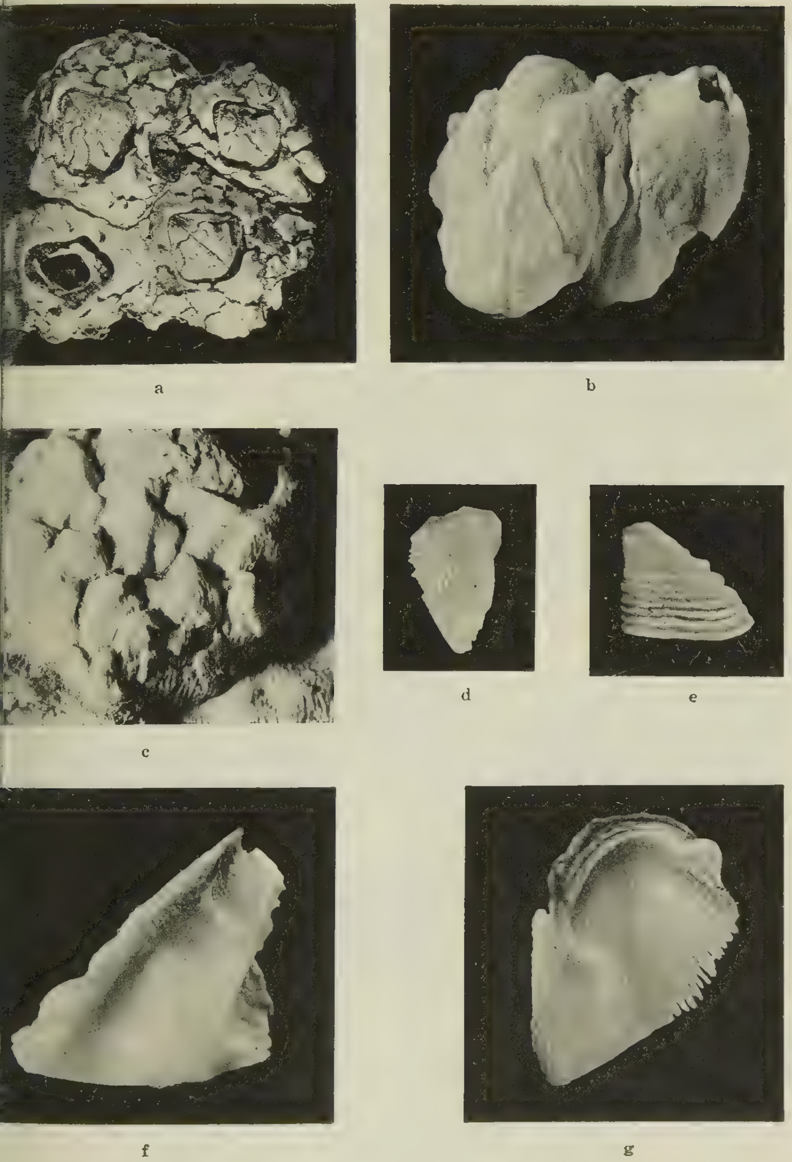


e I. *Catophragmus imbricatus* Sowerby. *a* Apical view, X2 ; *b* Rostral view of a young speci-
with *Tetraclita squamosa stalactifera* (Lamarck) on lateral, X6 ; *c* Lateral-carinal view
arge specimen, X4 ; *d-e* External views of opercular valves, X7; *f-g* Internal views of
rcular valves, X7. Photographs by Elizabeth A. McGraw and Eugene E. Collias.

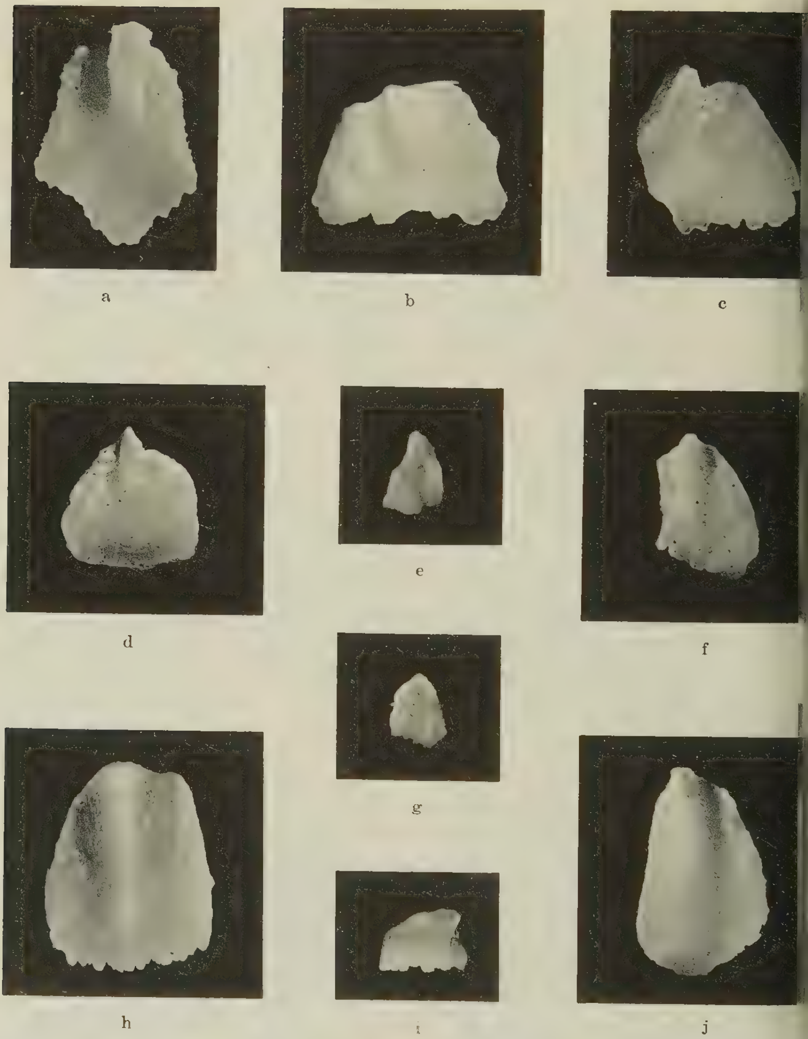
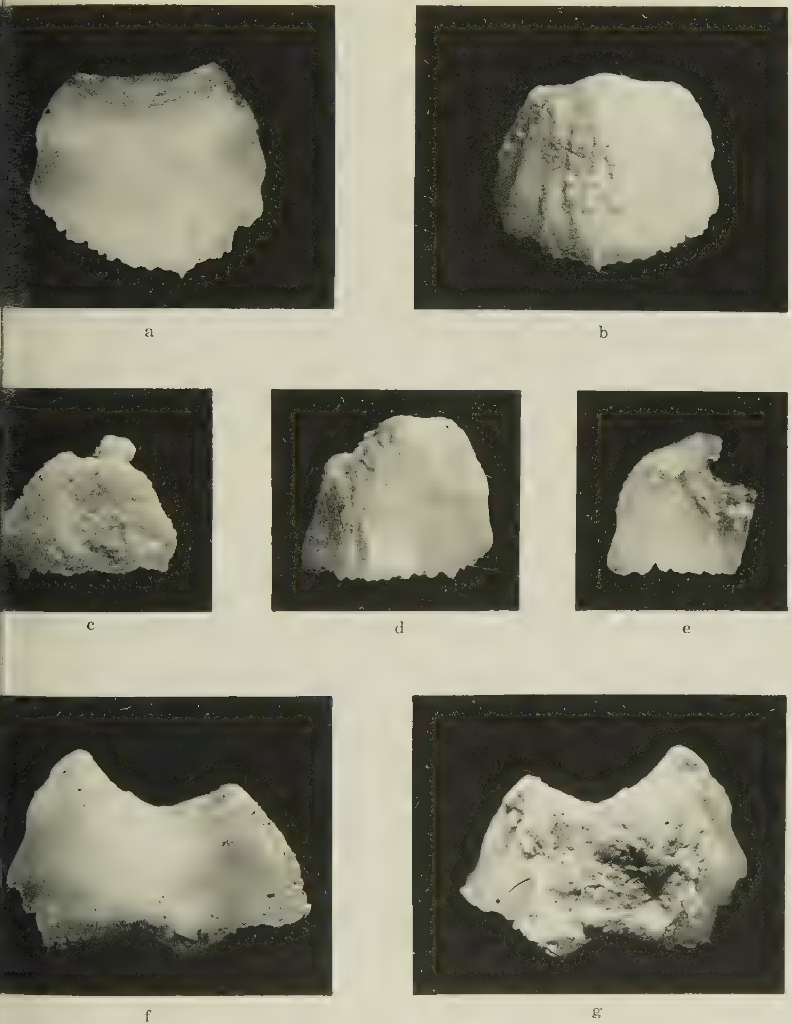


Plate II. *Catophragmus imbricatus* Sowerby, internal views, X7. *a-c* Left rostrolateral, lateral, and left carinolateral; *d-j* Supplementary plates: *d, h* like rostrum; *e, f, i, j* like lat or carinolaterals; *g* lateral edges beveled.



a b c d e f g

e III. *Catophragmus imbricatus* Sowerby, X7. *a-b* Internal and external views of rostrum; External views of right rostrolateral, left lateral and right carinolateral; *f-g* Internal and rnal views of carina.

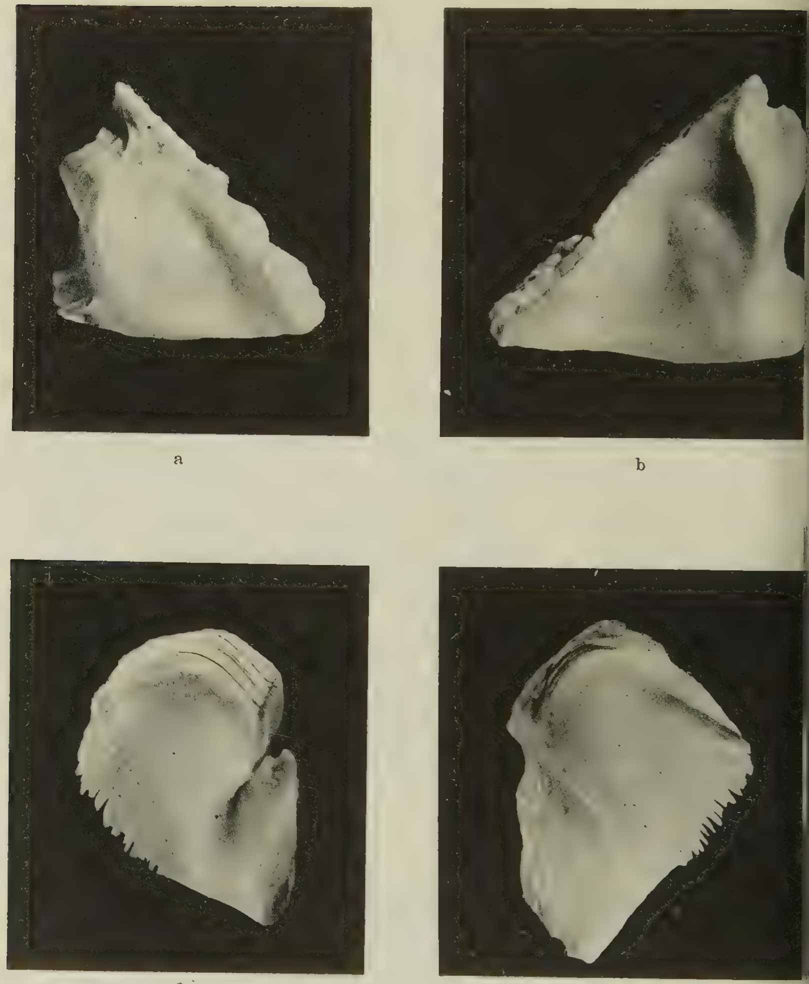
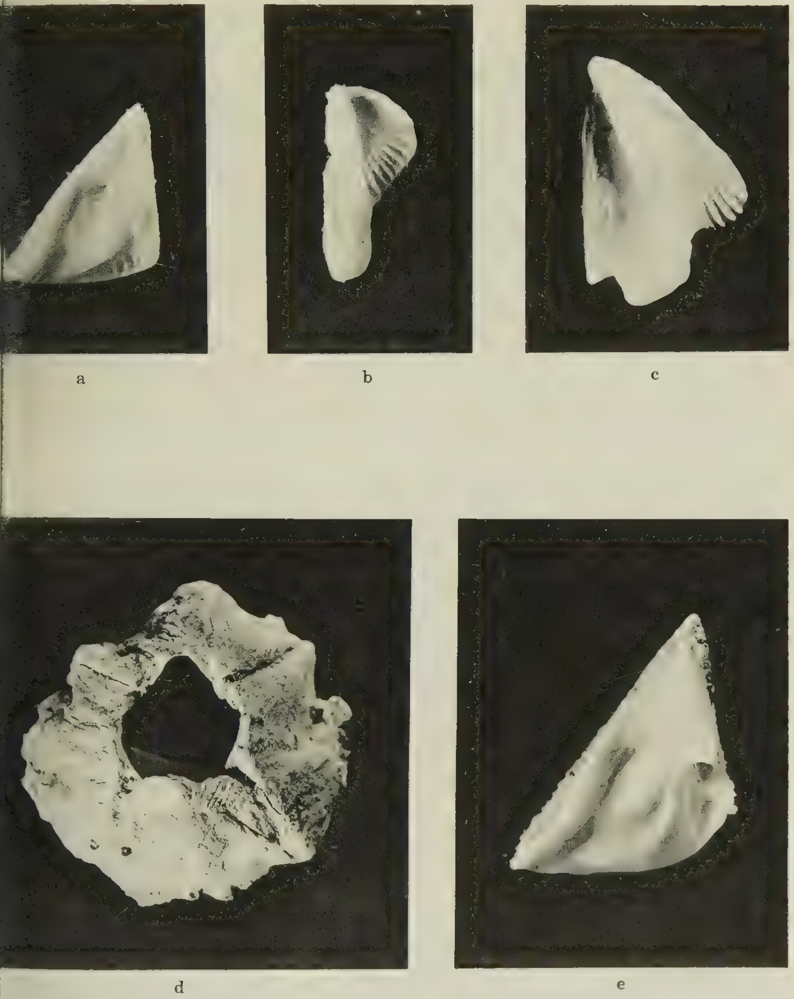


Plate IV. *Catophragmus imbricatus* Sowerby, X7. *a-d* Internal views of opercular valves mature specimen: *a-b* scuta; *c-d* terga.



e V. *Tetraclita squamosa stalactifera* (Lamarck). *a-b* Internal views of opercular valves, *Balanus amphitrite hawaiiensis* Broch. *c* and *e* Internal views of opercular valves (see Pl. and *g* for those of other side), X4 ; *d* Apical view, X2.

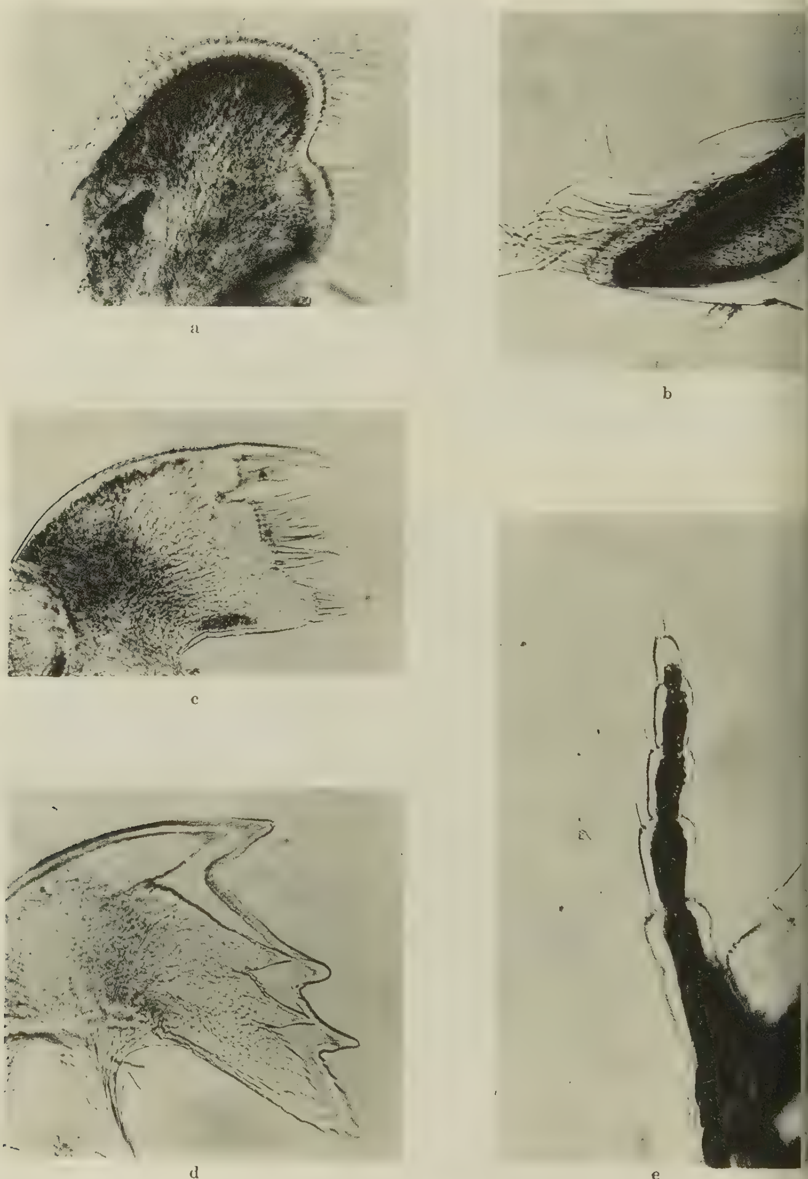
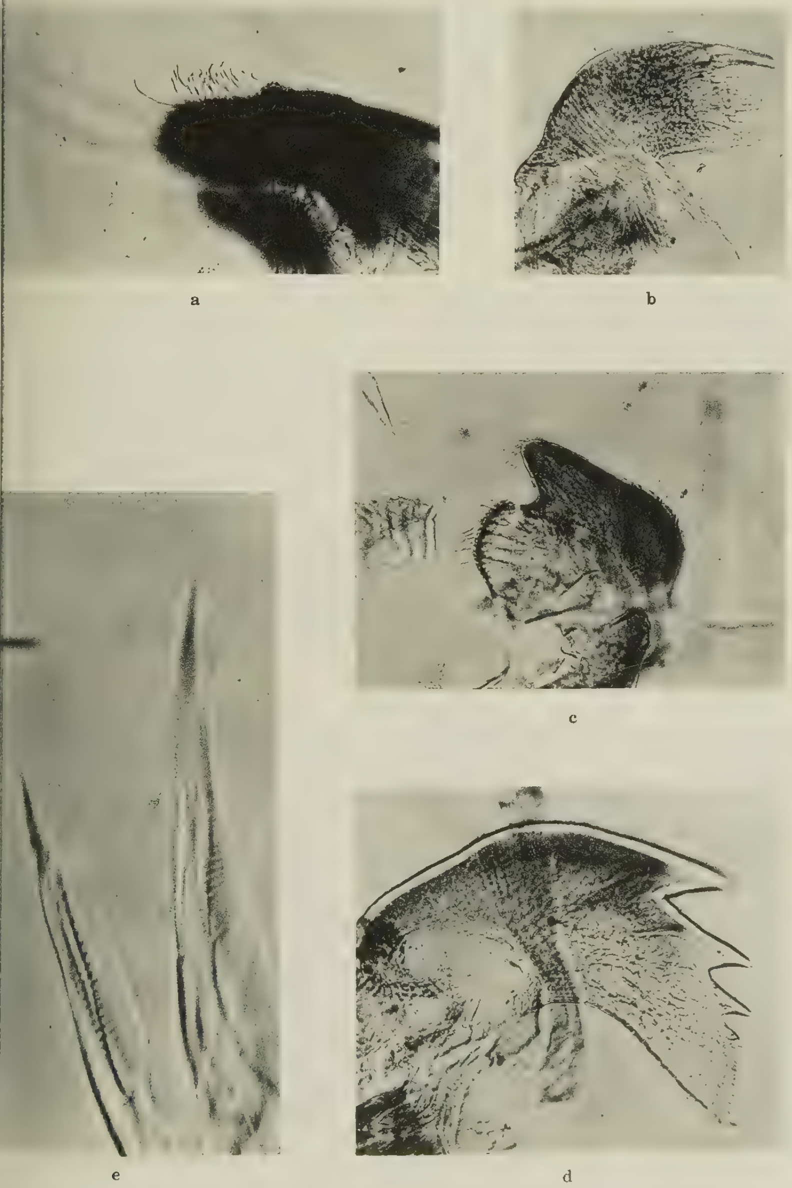
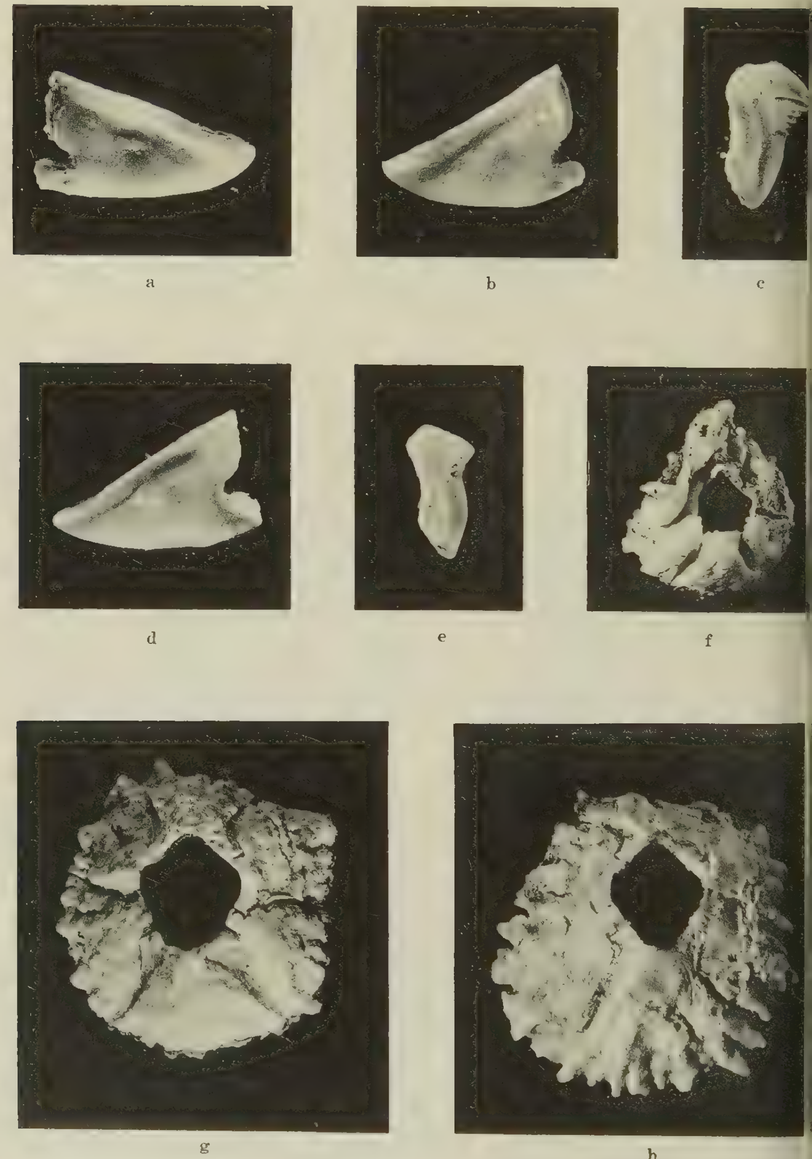

a b c d e

Plate VI. *Catophragmus imbricatus* Sowerby, X118. *a* Second maxilla; *b* Palp; *c* First max
d Mandible; *e* Caudal appendage.



VII. *Chthamalus stellatus thompsoni*, new subspecies. Mouth parts, X118: *a* First maxilla ;
lp; *c* Second maxilla ; *d* Mandible ; *e* Toothed spines of second cirrus, X1280.

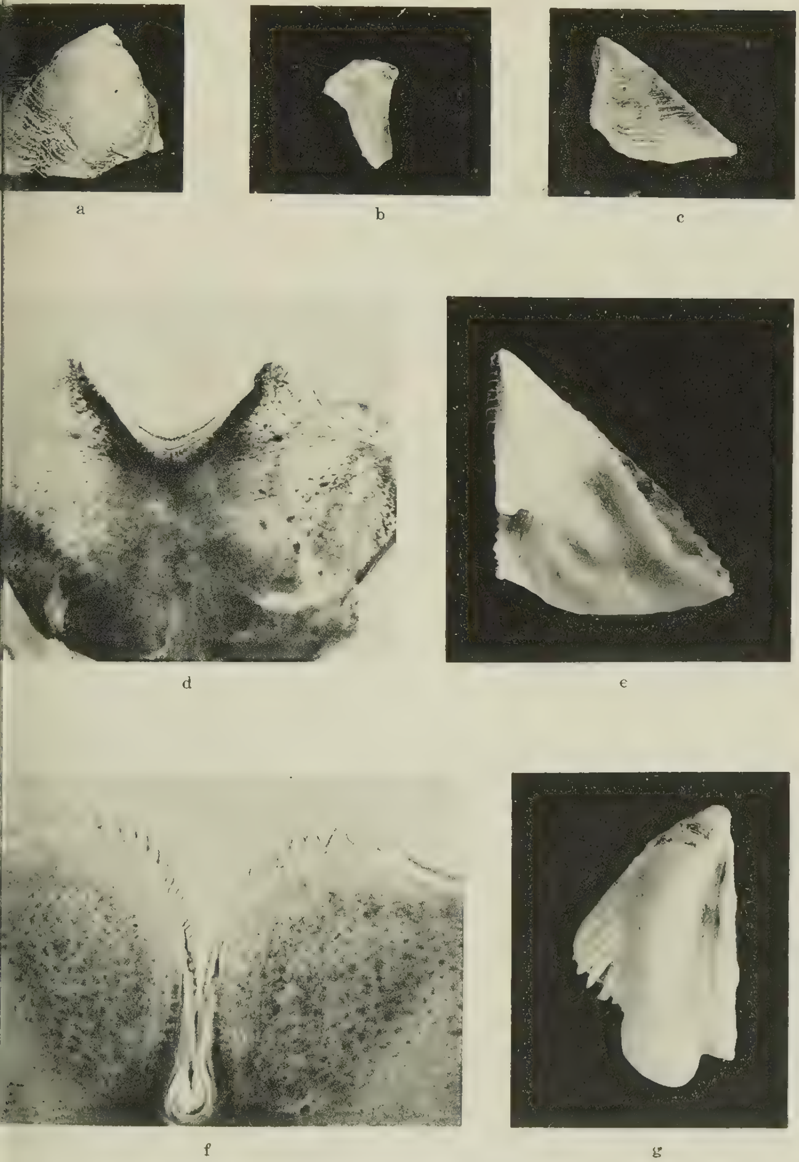


a b c

d e f

g h

Plate VIII. *Chthamalus stellatus thompsoni*, new subspecies. *a-c* Internal views of oper valves, X10; *d-e* Internal views of opercular valves of holotype, X10; *f* Apical view of corroded specimen, X5; *g* Apical view of holotype, X5; *h* Apical view, X5.



IX. *Chthamalus stellatus thompsoni*, new subspecies. *a-c* External views of rostrum and cular valves of a noncorroded specimen, X10; *d* Labrum, X118. *Balanus amphitrite iiensis* Broch. *e* and *g* Internal views of opercular valves, X4 (see Pl. 5, *c* and *e* for those her side); *f* Labrum, X180.

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BOUNDARIES IN THE THEORY OF OCEAN CURRENTS

By

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ABSTRACT

ribed in this paper is a technique of using artificial water boundaries in of ocean currents. As boundary values, geostrophic currents are suggested. chnique may hold promise for other applications in theoretical discussions an currents.

Boundaries in the Ocean. In order to simplify mathematical sis, theoretical discussions of ocean currents, excepting that unk and Carrier (1950), have been confined to rectangular or rilateral models. Serious difficulties arise when attempts are to expand these simplified conditions to actual oceans with ular boundaries.

cept near the Equator, geostrophic currents can be calculated the observed distribution of mass. But geostrophic currents, ractical approximations to actual currents, are inadequate if ust consider both vertical and horizontal friction, and we are with complicated boundary value problems.

the surface, velocity components are determined by obseron, or it is assumed that wind traction balances surface stress. solid coastal boundaries, velocities perpendicular to such daries must vanish, and, in the presence of lateral eddy viscosmotion parallel to them must vanish also. These boundary itions can be used for any part of an ocean bounded by coasts. t we still have to propound boundary conditions where the dary is water, and this paper attempts to show that we can ably compute the horizontal flow pattern in a water-bound ngular or quadrilateral ocean.

Geostrophic Boundary Conditions. In a previous paper (Hidaka Nagata, 1958), it was shown that, in a section without coastal daries, the geostrophic currents closely approximate the actual nts and that these geostrophic current velocities provide us with convenient boundary conditions. Since the geostrophic f only approximates the true circulation, it is desirable to der differential equations in which boundary conditions are of mini importance.

3. *Theory*. Taking the x-axis eastward and the y-axis northwa and assuming a given pressure distribution in a sea surface sw by prevailing winds, the hydrodynamic equations of stationary oc currents are expressed by

$$\left.\begin{aligned} A_l\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\mu\frac{\partial^2 u}{\partial z^2}+2\,\omega\sin\varphi\varrho\, v &= \frac{\partial p}{\partial x}; \\ A_l\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\mu\frac{\partial^2 v}{\partial z^2}-2\,\omega\sin\varphi\varrho\, u &= \frac{\partial p}{\partial y}; \end{aligned}\right\}$$

where u and v are components of current velocity parallel to x-axis and y-axis, p is the pressure, μ and A_l are the coefficient vertical and lateral eddy viscosity, ϱ is the density of sea wa ω is the angular velocity of the earth, and φ is the geograp latitude.

Now let u and v represent components of a current relative t certain reference level $z = h$. Then both $\partial p/\partial x$ and $\partial p/\partial y$ are ferred to the same reference level.

If we multiply the second part of (1) by $i = \sqrt{-1}$ and add product to the first part,

$$A_l\left(\frac{\partial^2 \overline{W}}{\partial x^2}+\frac{\partial^2 \overline{W}}{\partial y^2}\right)+\mu\frac{\partial^2 \overline{W}}{\partial z^2}-i\,2\,\omega\sin\varphi\varrho\,\overline{W} = \frac{\partial p}{\partial x}+i\frac{\partial p}{\partial y},$$

where

$$\overline{W} = u+iv.$$

On the surface ($z = 0$) we have

$$z = 0; \quad -\mu\frac{\partial \overline{W}}{\partial z} = \tau_x + i\tau_y,$$

and at the reference level ($z = h$) we have

$$z = h: \quad \overline{W} = 0.$$

n the water boundaries, $x = 0$, a and $y = 0$, b, geostrophic cur- s are computed from mass distribution. In mathematical lang- , we have

$$\left.\begin{array}{l} \text{(1) at the boundary } x = 0 \\ \qquad \overline{W} = G(0, y, z); \\ \text{(2) at the boundary } x = a \\ \qquad \overline{W} = G(a, y, z); \\ \text{(3) at the boundary } y = 0 \\ \qquad \overline{W} = G(x, 0, z); \\ \text{(4) at the boundary } y = b \\ \qquad \overline{W} = G(x, b, z), \end{array}\right\} \tag{6}$$

re $G(x, y, z)$ represents the geostrophic current at x, y, and z. ow, if D represents the geopotential distance over the reference ace,

$$\frac{\partial p}{\partial x} + i\frac{\partial p}{\partial y} = \varrho\left(\frac{\partial D}{\partial x} + i\frac{\partial D}{\partial y}\right),$$

the distribution of D gives the so-called relative dynamic topo- phy. Then

$$\frac{A_l}{\varrho}\left(\frac{\partial^2 \overline{W}}{\partial x^2} + \frac{\partial^2 \overline{W}}{\partial y^2}\right) + \frac{\mu}{\varrho}\frac{\partial^2 \overline{W}}{\partial z^2} - i\,2\,\omega \sin\varphi\,\overline{W} = \frac{\partial D}{\partial x} + i\frac{\partial D}{\partial y} \tag{7}$$

h the boundary conditions (4), (5) and (6).

ow it is possible to expand $\overline{W}$ and D in a series of forms:

$$\left.\begin{array}{l} \overline{W}(x, y, z) = \sum\limits_n \overline{W}_n(x, y) \cos\dfrac{(2n-1)\pi z}{2h}, \\ \text{re} \\ \overline{W}_n(x, y) = \dfrac{2}{h}\displaystyle\int_0^h \overline{W}(x, y, \zeta) \cos\dfrac{(2n-1)\pi\zeta}{2h}\, d\zeta; \end{array}\right\} \tag{8}$$

$$\left.\begin{array}{l} D(x, y, z) = \sum\limits_n D_n(x, y) \cos\dfrac{(2n-1)\pi z}{2h}, \\ \text{re} \\ D_n(x, y) = \dfrac{2}{h}\displaystyle\int_0^h D(x, y, \zeta) \cos\dfrac{(2n-1)\pi\zeta}{2h}\, d\zeta. \end{array}\right\} \tag{9}$$

Further assume

$$\frac{\mu}{\varrho}\frac{\partial^2 \overline{W}}{\partial z^2} = \sum_n \cos\frac{(2n-1)\,\pi z}{2h}\cdot\frac{2}{h}\int_0^h \frac{\mu}{\varrho}\frac{\partial^2 \overline{W}}{\partial \zeta^2}\cos\frac{(2n-1)\,\pi\zeta}{2h}\,d\zeta;$$

then, by Stokes method,

$$\frac{2}{h}\int_0^h \frac{\mu}{\varrho}\frac{\partial^2 \overline{W}}{\partial \zeta^2}\cos\frac{(2n-1)\,\pi\zeta}{2h}\,d\zeta = \frac{2}{h}(\tau_x + i\,\tau_y) - \frac{(2n-1)^2\pi^2\mu}{4h^2\varrho}\,\overline{W}_n(x, y$$

therefore

$$\frac{\mu}{\varrho}\cdot\frac{\partial^2 \overline{W}}{\partial z^2} = \sum_n \left\{\frac{2}{h}(\tau_x + i\,\tau_y) - \frac{(2n-1)^2\pi^2\mu}{4h^2\varrho}\,\overline{W}_n(x, y)\right\}\cos\frac{(2n-1)\,\pi z}{2h}.\,($$

Substituting (8), (9) and (10) in (7), we have an equation $\overline{W}_n(x, y)$ as follows:

$$\left.\begin{aligned}\frac{A_l}{\varrho}\left(\frac{\partial^2 \overline{W}_n}{\partial x^2} + \frac{\partial^2 \overline{W}_n}{\partial y^2}\right) - \left\{\frac{(2n-1)^2\pi^2\mu}{4h^2\varrho} + i\cdot 2\,\omega\sin\varphi\right\}\overline{W}_n & \\ = \frac{\partial D_n}{\partial x} + i\,\frac{\partial D_n}{\partial y} - \frac{2}{h\varrho}(\tau_x + i\,\tau_y). &\end{aligned}\right\} \quad ($$

$$(n = 1, 2, 3, \ldots)$$

Now we have a close relationship

$$\begin{aligned} d^2\cdot\left(\frac{\partial^2 \overline{W}_n}{\partial x^2} + \frac{\partial^2 \overline{W}_n}{\partial y^2}\right) &= \overline{W}_n(x+d, y) + \overline{W}_n(x-d, y) \\ &+ \overline{W}_n(x, y+d) + \overline{W}_n(x, y-d) - 4\overline{W}_n(x, y),\end{aligned}$$

where d is the distance from a point (x, y) to the four neighbor points—north, south, east and west. Applying this rule to (11)

$$\left.\begin{aligned}&\overline{W}_n(x+d, y) + \overline{W}_n(x-d, y) + \overline{W}_n(x, y+d) + \overline{W}_n(x, y-d) \\ &- \left\{4 + \frac{(2n-1)^2\pi^2}{4}\left(\frac{d}{h}\right)^2\cdot\frac{\mu}{A_l} + i\,\frac{2\,\omega\,\varrho\,d^2}{A_l}\cdot\sin\varphi\right\}\cdot\overline{W}_n(x, y) \\ &= \left(\frac{\partial D_n}{\partial x} + i\,\frac{\partial D_n}{\partial y}\right)\cdot\frac{\varrho\,d^2}{A_l} - \frac{2\,d^2}{h\cdot A_l}(\tau_x + i\,\tau_y).\end{aligned}\right\} \quad ($$

the sum of the four values of $\overline{W}$ at four neighboring points is
esented by $\Sigma\,\overline{W}$

$$\left.\begin{aligned}&+\frac{(2n-1)^2\pi^2}{4}\cdot\left(\frac{d}{h}\right)^2\cdot\frac{\mu}{A_l}+i\,\frac{2\,\omega\,\varrho\,d^2}{A_l}\cdot\sin\varphi\Big\}\,\overline{W}_n\\&=\left(\frac{\partial D_n}{\partial x}+i\,\frac{\partial D_n}{\partial y}\right)\cdot\frac{\varrho\,d^2}{A_l}-\frac{2\,d^2}{h\cdot A_l}(\tau_x+i\,\tau_y)-\Sigma\,\overline{W}_n.\end{aligned}\right\}\qquad(13)$$

$$(n=1,2,3,\ldots)$$

w it is easy to show that this equation can be solved by iter-
if the boundary values are given. If $\overline{W}_n^{(m)}$ gives the m th
oximation of $\overline{W}_n$ at (x, y), then the $(m+1)$ th approximation
$\overline{V}_n^{(m+1)}$ will be given by

$${}^{+1)} = -\frac{\left(\dfrac{\partial D_n}{\partial x}+i\,\dfrac{\partial D_n}{\partial y}\right)_{x,y}\cdot\dfrac{\varrho\,d^2}{A_l}-(\tau_x+i\,\tau_y)\cdot\dfrac{2\,d^2}{hA_l}-\Sigma\,\overline{W}_n^{(m)}}{4-\dfrac{(2n-1)^2\pi^2}{4}\left(\dfrac{d}{h}\right)^2\cdot\dfrac{\mu}{A_l}+i\,\dfrac{2\,\omega\,\varrho\,d^2}{A_l}\sin\varphi_{x,y}}.\qquad(14)$$

e process must be started from points next to the boundaries
re the values of $\overline{W}_n$ are given, so that the boundary values may
involved in $\Sigma\,\overline{W}_n$. The values which $\overline{W}_n$ should take at the
ndaries, $G_n(0,y)$, $G_n(a,y)$, $G_n(x,0)$ and $G_n(x,b)$, will be ob-
ed by expanding the geostrophic currents at the vertical planes
0, a and $y = 0$, b, also in similar series, or

$$\left.\begin{aligned}G(0,y,z)&=\sum_n G_n(0,y)\cos\frac{(2n-1)\pi z}{2h},\\G(a,y,z)&=\sum_n G_n(a,y)\cos\frac{(2n-1)\pi z}{2h},\\G(x,0,z)&=\sum_n G_n(x,0)\cos\frac{(2n-1)\pi z}{2h},\\G(x,b,z)&=\sum_n G_n(x,b)\cos\frac{(2n-1)\pi z}{2h}.\end{aligned}\right\}\qquad(15)$$

fter a number of iteration processes, the values of $\overline{W}_n^{(m)}(x,y)$
converge to a definite set of values, or

$$\overline{W}_n(x,y) = \lim_{m\to\infty} \overline{W}_n^{(m)}(x,y).$$

It is evident that the convergence of $\overline{W}_n^{(m)}(x,y)$ will be obta more quickly when the ratio

$$\frac{\Sigma\,\overline{W}_n}{\left(\frac{\partial D_n}{\partial x} + i\,\frac{\partial D_n}{\partial y}\right)_{x,y}\cdot\frac{\varrho\, d^2}{A_l} - (\tau_x + i\,\tau_y)\cdot\frac{2\,d^2}{hA_l}\cdot\sin\varphi_{x,y}}$$

is smaller, or if

$$\left|\frac{(2\,n-1)^2\pi^2}{4}\cdot\left(\frac{d}{h}\right)^2\cdot\frac{\mu}{A_l} + i\,\frac{2\,\omega\varrho\, d^2}{A_l}\cdot\sin\varphi_{x,y}\right|$$

is larger.

Thus the smaller the value of A_l, the faster the convergenc the iteration. But we can show that successive approximat necessarily lead to a final convergence.

In this process, the boundary values will have less and les fluence on $\overline{W}_n$ as they recede from the boundaries. This permits use of geostrophic current velocities for the boundary values, only slight influence on the final results.

4. *Zonal Flow: Mid-Pacific Equatorial Current System.* App tion of the present idea is best demonstrated in the case of z flow. In the equatorial region of the mid-Pacific, where the w moves mostly in an E-W direction, the dynamic equations wil reduced to two dimensions. Assume a zonal flow perpendicula a meridional section extending from $y = 0$ to $y = b$ and pas through the Equator (Fig. 1 B). Further, neglect the change u, v, and p in the x-direction. The dynamic equations (1), (2 (7) then reduce to

$$\frac{A_l}{\varrho}\frac{\partial^2\overline{W}}{\partial y^2} + \frac{\mu}{\varrho}\frac{\partial^2\overline{W}}{\partial z^2} - i\cdot 2\,\omega\sin\varphi\,\overline{W} = i\,\frac{\partial D}{\partial y}.$$

The boundary conditions to be satisfied at the surface and at reference layer $z = h$ remain the same, being given by

$$z = 0: -\mu\frac{\partial\overline{W}}{\partial z} = \tau_x + i\,\tau_y$$

and

$$z = h: \overline{W} = 0.$$

both ends of this meridional section we have

$$y = 0: \qquad \overline{W}(0,z) = G(0,z) = \sum_n G_n(0) \cos \frac{(2n-1)\pi z}{2h},$$

$$y = b: \qquad \overline{W}(b,z) = G(b,z) = \sum_n G_n(b) \cos \frac{(2n-1)\pi z}{2h},$$

re $G(0, z)$ and $G(b, z)$ are geostrophic currents at both ends of profile, which can easily be computed from observed mass bution.

plying the same operation as that above, we have a similar ession to (14), or

$$ {}^{+1)}(y) = -\frac{i\left(\frac{\partial D_n}{\partial y}\right)\cdot\frac{\varrho d^2}{A_l}\cdot(\tau_x + i\tau_y) - \frac{2d^2}{hA_l}\left\{\overline{W}_n^{(m)}(y+d) + \overline{W}_n^{(m)}(y-d)\right\}}{2 + \frac{(2n-1)^2\pi^2}{4}\cdot\left(\frac{d}{h}\right)^2\cdot\frac{\mu}{A_l} + i\,\frac{2\omega\varrho d^2}{A_l}\cdot\sin\varphi_y}. \qquad (20)$$

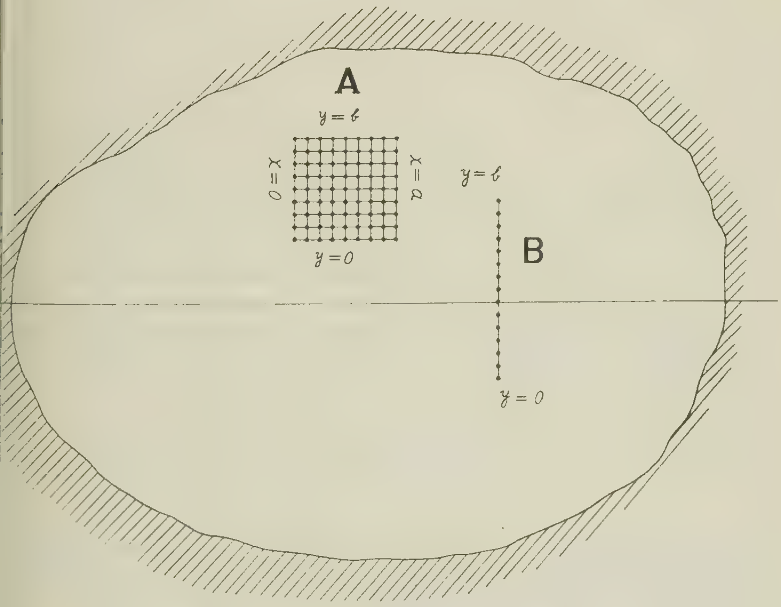


Figure 1. Water boundaries in an ocean.

For starting values of 0th approximations, we employ

$$\overline{W}_n^{(0)}(y) = -\frac{i\left(\dfrac{\partial D_n}{\partial y}\right)_y \cdot \dfrac{\varrho d^2}{A_l} - (\tau_x + i\tau_y)\cdot\dfrac{2d^2}{hA_l}}{2 + \dfrac{(2n-1)^2\pi^2}{4}\cdot\left(\dfrac{d}{h}\right)^2\cdot\dfrac{\mu}{A_l} + i\,\dfrac{2\,\omega\varrho\, d^2}{A_l}\sin\varphi_y},$$

but it is possible to find better approximations by using the currence expression (20). In this case, values of $\overline{W}_n(y)$ at both of the profile are always given by

$$\left.\begin{aligned}\overline{W}_n(0) &= -\frac{i\left(\dfrac{\partial D_n}{\partial y}\right)_0 \cdot \dfrac{\varrho d^2}{A_l} - (\tau_x + i\tau_y)_0\cdot\dfrac{2d^2}{h\cdot A_l}}{2 + \dfrac{(2n-1)^2\pi^2}{4}\cdot\left(\dfrac{d}{h}\right)^2\cdot\dfrac{\mu}{A_l} + i\,\dfrac{2\,\omega\varrho\, d^2}{A_l}\sin\varphi_0}\\ &\text{and}\\ \overline{W}_n(b) &= -\frac{i\left(\dfrac{\partial D_n}{\partial y}\right)_b \cdot \dfrac{\varrho d^2}{A_l} - (\tau_x + i\tau_y)_b\cdot\dfrac{2d^2}{h\cdot A_l}}{2 + \dfrac{(2n-1)^2\pi^2}{4}\cdot\left(\dfrac{d}{h}\right)^2\cdot\dfrac{\mu}{A_l} + i\,\dfrac{2\,\omega\varrho\, d^2}{A_l}\sin\varphi_b}.\end{aligned}\right\}$$

5. *Application to the Equatorial Undercurrent.* Let us apply theory to previous mid-Pacific observations (Cromwell, 1951); profile extends over 20 stations approximately along 172° W 5° S to 15° N (Sts. 26 to 6, M/V HUGH M. SMITH's Cruise II, Janu March 1950); the stations are spaced at intervals of 1° latitude, of them always being located at the Equator. This gives $d = 111.12$

The geopotential distances are given for 17 depths: 0, 10, 20 50, 75, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800 and 100 and the dynamic heights over the 1000 db-surface were calcul and analyzed according to the series:

$$D(y,z) = \sum_n D_n(y)\cos\frac{(2n-1)\pi z}{2h}.$$

It has been determined that D is well represented by this seri we use the 17 levels noted above. Then the meridional slopes be calculated by taking successive differences of D and divi them by d.

s for the wind stress τ_x and τ_y, these were calculated from Munk's
7) formula based on wind observations taken on the same cruise.
tly speaking, we probably should have used the synoptic
ibution of wind stresses for the season in which the observations
taken, but it was more convenient to use the data taken on
d simultaneously with the hydrographic casts.

is most difficult to choose a reasonable set of values for A_l
μ. Previous authors found from different sources that A_l varies
10^7 through 10^9 and that μ/A_l is about 10^{-6}. Thus it is suffi-
t to try the values 10^7, 10^8 and 10^9 for A_l in combination with
values of μ/A_l 10^{-7}, 10^{-6}, 10^{-5}, etc.

Zonal Flow as Influenced by A_l and μ. Note that the calculated
ion of zonal flow depends largely on a combination of the values
$_l$ and μ, seven of which have been tried. Of these, four combin-
ns ($A_l = 10^8$, $\mu = 10$), ($A_l = 10^8$, $\mu = 10^3$), ($A_l = 10^7$, $\mu = 1$),
($A_l = 10^7$, $\mu = 10^2$) gave a calculated zonal velocity exceeding
cm/sec, which values are contrary to observation. Fig. 2, which
ws the meridional variation of surface zonal velocities computed
several combinations of A_l and μ, demonstrates that the above-
ntioned four pairs give quite unrealistic zonal velocities near the
uator. Therefore we shall discuss here the results of only three
er combinations (1) $A_l = 10^9$ c.g.s., $\mu = 10^2$ c.g.s. (2) $A_l = 10^8$
s., $\mu = 10^2$ c.g.s. and (3) $A_l = 10^8$ c.g.s., $\mu = 10^3$ c.g.s. (Figs. 3,
and 5).

1) Regarding the result for $A_l = 10^9$ c.g.s., $\mu = 10^2$ c.g.s., $\mu/A_l =$
$^{-7}$, Figs. 3, 4 and 5 give the dynamic section of these isovels for
three combinations of A_l and μ chosen above. $A_l = 10^9$ c.g.s.,
10^2 c.g.s. gives a fairly reasonable result, with the distribution
sovels approximately similar to that observed by the Hawaiian
anographers except that the absolute values of velocities seem
ttle lower and that the Equatorial Undercurrent is located some-
at more to the north than would be expected. The depth of the
e of the Undercurrent also appears deeper than that observed,
this can be explained as a consequence of the assumption that
constant from surface to bottom. It appears that $A_l = 10^9$ c.g.s.
lightly large.

2) The result for $A_l = 10^8$ c.g.s., $\mu = 10^2$ c.g.s., $\mu/A_l = 10^{-6}$
g. 4) gives a strong current (> 180 cm/sec) at about 2° S, a fact
trary to observation, and a faint eastward flow or a counter

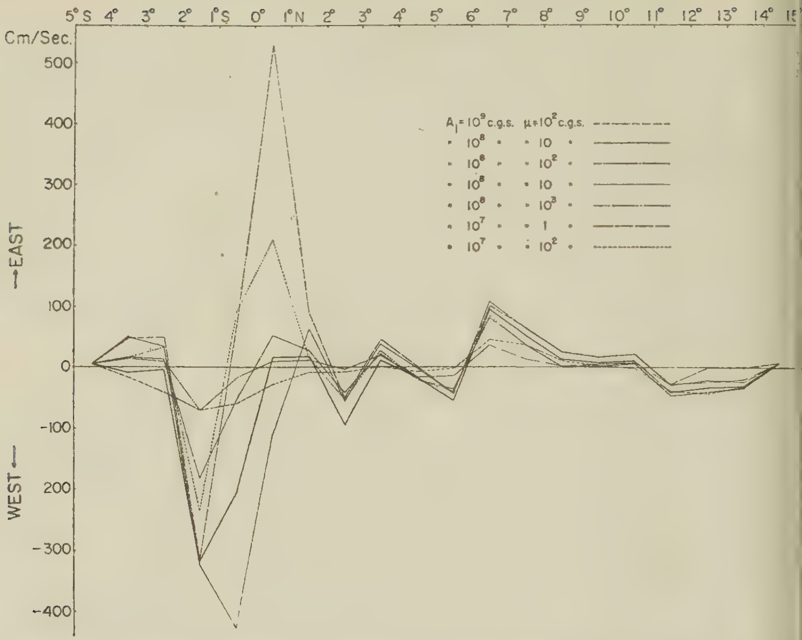


Figure 2. Variation of surface zonal velocities across the meridional section of 172 computed for several pairs of values of A_l and μ.

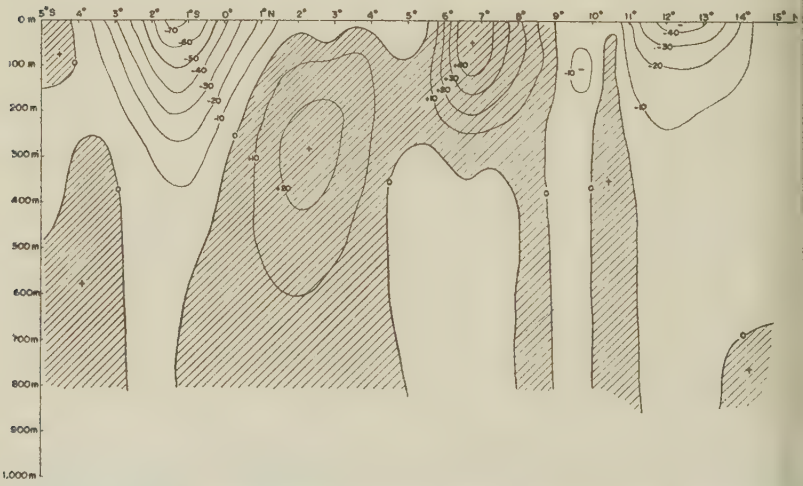
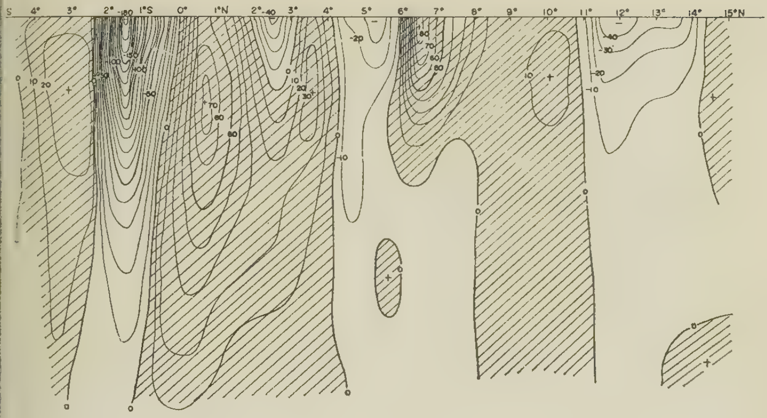
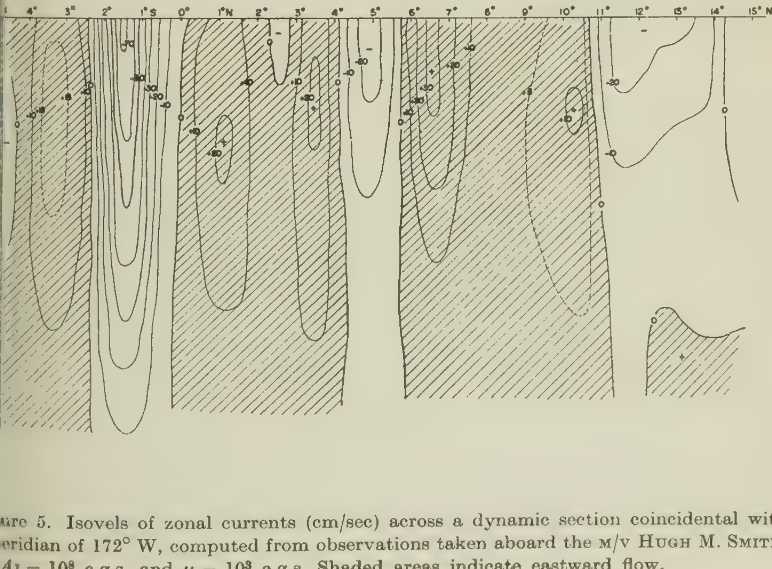


Figure 3. Isovels of zonal currents (cm/sec) across a dynamic section coincidental the meridian of 172° W, computed from observations taken aboard the M/V Hugh M. Sm $A_l = 10^9$ c.g.s. and $\mu = 10^2$ c.g.s. Shaded areas indicate eastward flow.



re 4. Isovels of zonal currents (cm/sec) across a dynamic section coincidental with eridian of 172° W, computed from observations aboard the M/V HUGH M. SMITH, $A_l = 10^8$ c.g.s. and $\mu = 10^2$ c.g.s. Shaded areas indicate eastward flow.



ure 5. Isovels of zonal currents (cm/sec) across a dynamic section coincidental with eridian of 172° W, computed from observations taken aboard the M/V HUGH M. SMITH, $A_l = 10^8$ c.g.s. and $\mu = 10^3$ c.g.s. Shaded areas indicate eastward flow.

current is seen at Lat. 3° or 4° S. Here the Equatorial Undercur
is shifted to the south, occupying just about the same posi
determined by previous observation.

(3) The result for $A_l = 10^8$ c.g.s., $\mu = 10^3$ c.g.s., $\mu/A_l =$
(Fig. 5) gives an Equatorial Undercurrent that is too weak (al
15 cm/sec). Moreover, there are weak eastward flows in the sur
layers south of the Equator. Thus $\mu = 10^3$ c.g.s. may be too l

In the last two cases, the Equatorial Undercurrent rises u
the surface layers, but this of course is contrary to observatio
this longitude.

These three sections, calculated for different combinations o
and μ, suggest that the most probable values of A_l will be so
where between 10^8 and 10^9 and that μ will be about 10^{-6}.
reasonable results will be obtained by a more accurate choic
values for A_l and μ.

These calculations indicate that the Equatorial Undercurrent
be explained as a joint action of wind stresses on the surface
planetary vorticity, and of a meridional pressure gradient.

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ORGANIC MATTER IN SEA WATER; AN EVALUATION OF VARIOUS METHODS FOR ISOLATION[1]

By

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ABSTRACT

e methods of isolating organic materials from salt solutions are evaluated for
ability in separating organic and inorganic constituents of sea water. A C^{14}-
ed aged algae culture was used as a test solution to determine the effectiveness
rious methods of isolating total dissolved organic material. Organic compounds,
n to be involved in biological metabolism, were also added to natural sea
r to determine the effectiveness of various methods in isolation. Results show
electrodialysis is effective for large molecule separation; liquid-liquid extraction
phenol, 2,4-lutidine, ethyl acetate, and benzyl alcohol removes substantial
tities of organic material. Coprecipitation with iron is a promising method in
95 % or more of the total organic material can be removed in this manner.
oval of the remnant iron without altering the organic material presents some
lems. Carbon and other absorbents are effective in separating organic and
ganic materials, but recovery from the adsorbents is difficult.

INTRODUCTION

ack of reliable methods to characterize and estimate quanti-
vely the soluble organic compounds present in various water
sses of the sea has long interfered with a true understanding of
chemical and ecological significance of these compounds (John-
, 1955). To approach a fuller comprehension of these relationships,
h purity organic concentrates isolated from sea water are neces-
y. However, since the ratio of organic to inorganic materials in
water is of the order of 10^{-4}, simple concentration is impractical.
s paper comprises a description and evaluation of five methods

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of separation which are straightforward applications of nor
methods for isolating organic compounds or of methods develo
in an attempt to provide useful means of studying this probl
The isolation techniques investigated are: (1) dialysis, (2) adso
tion of organic constituents on various materials, such as carb
clay, cellulose, etc., (3) ion-exchange of organic constituents
resins, (4) solvent extraction of organic materials with selec
solvents, and (5) coprecipitation with proper inorganic salts.

In this study little or no attempt is made to relate the result
the organic material in natural sea water. Rather, the work c
centrates on: (1) Determining the applicability of various proce
in isolating total *dissolved* organic matter from an aged algae
ture grown in the laboratory in fertilized natural sea water;
culture was grown in C^{14}-labeled carbon dioxide system, and
resulting filtrate provided C^{14}-labeled samples of constant orga
composition so that methods could be compared; (2) Evaluat
various methods for isolation of added organic compounds of kno
biological significance from natural sea water; (3) Obtaining i
dental information on the character of organic constituents isola
from the filtered algae culture and natural sea water.

Previous Work on Concentration and Character of Organic Ma
Analyses given in the literature show that the concentration
dissolved organic carbon in the ocean is between one and five m
Plunkett and Rakestraw (1955) have reported that uniform dist
ution, either vertical or horizontal, is nonexistent. A minimum
organic carbon was found at one station in the Pacific (40°34
170°2′ E) between 450 and 700 m in deep waters of the Pacific
at a depth which roughly corresponds to the oxygen-minim
layer. Other stations showed little correlation. According to Niel
(1955) there is an estimated 15 kg of soluble organic matter bene
each square meter of ocean surface, with the total dissolved car
exceeding the amount of particulate matter present. The poss
sources of soluble organic matter are: (1) decomposing organis
(2) compounds secreted or excreted by living organisms in
course of their metabolism, (3) land sources, and (4) sediments,
exchange or decomposition processes. The decomposition of orga
matter is slow in the ocean itself, but in bottles, where surface a
is available for bacterial action (ZoBell, 1943), 25–50 $^0/_0$ of the
ganic material in sea surface water is readily decomposed. Ap

y some organic substances in sea water resist decomposition
bacteria indefinitely, thus some deep sea organic compounds
be thousands of years old (Nielsen, 1955).

allentyne (1957) has summarized available data regarding the
cular nature of soluble organic compounds isolated from sea
r. Wangersky (1952) reported dehydroascorbic acid from Gulf
exico waters as well as isolation of what appeared to be a rham-
de in concentrations of as much as 0.1 g/l. Lewis and Rakestraw
) reported a concentration of 0 to 10 mg/l of total carbohydrate
e Pacific Ocean, and Hargreaves, *et al.* (1951) and Creach (1955)
nstrated the presence of citric and malic acids in the sea. Fogg
) postulated that pentose units may be present in marine and
water, and that certain blue green algae secrete peptides,
les, and pentoses. Krogh (1934) believed that dissolved organic
ter in fresh and sea water consists principally of substances of
trogenous nature and of pentosans and that 80 to 90 $^0/_0$ of the
nic compounds come from autolysis of dead organisms. Pratt
4) and Nielsen (1955) demonstrated that antibiotics are given
by some algae; Cowey (1956) extracted soluble vitamin B_{12}
sea water in the North Sea and English Channel.

vidence for Significance of Organic Matter. Considerable evidence
ch indicates the significance of organic matter in the sea has
accumulated (Lucas, 1955; Johnson, 1955; Saunders, 1957).
arly as 1935, Allison and Cole showed that feeding movements
barnacles can be correlated with abundance of dinoflagellates,
probably with their metabolic by-products. Collier, *et al.* (1950,
3) found that the pumping rate of the oyster is influenced by a
stance in the water which reacts to the carbazole test, and that
or response was stimulated in barnacles and oysters by niacin-
de and ascorbic acid. Wilson and Armstrong (1952, 1954) reared
chaete and echinoderm larvae in water from various locations
er the same physical conditions and found differences in growth
s; the growth of the larvae was retarded when the water was
eated, indicating the presence of volatile growth-stimulating
stances.

asler and Wisby (1951) obtained evidence that minnows were
to discriminate between the waters of two Wisconsin creeks
r conditioning. Cautery of the olfactory epithelia rendered them
esponsive; however, they reacted to the distillate rather than

the residue after the water had been vacuum distilled at 25 Alderdice, *et al.* (1954) have given evidence of extreme sensiti of migrating salmon to extracts of mammalian skin. Thus i reasonable to assume that organic compounds may influence movement of fish in seeking food, in locating spawning areas even in avoiding danger.

The soluble organic matter in fresh and sea water apparei serves as a source of energy for some organisms whereas for othe serves as growth or behavior stimuli or as an essential growth fac Organic matter may form organic complexes with trace metals wl may be beneficial or detrimental. Dissolved organic matter may present in the form of toxins which inhibit or kill organisms (Sa ders, 1957). The success of some algae, bacteria, and fungi may predicted and their ecological succession determined on the b of the organic materials present.

Lucas (1955) not only summarized and emphasized the kno ecological significance of "external metabolites" on the distribu and growth of marine algae, bacteria, fungi, and protozoans focussed attention on the effects of natural organic substances the physical responses of marine worms, echinoderms, mollu crustaceans, and fish. Saunders (1957) also presented a sim summary of the significance of dissolved organic material to ph plankton.

Hood and Jeffrey (1957) have recently shown that, in ph synthesis, *Nitzschia closterium*, *Porphyridium cruentum*, and *Pl monas* sp. utilize CO_2 from carbamino carboxylic acid comple (synthesized from alanine or from organic compounds isolated f sea water) in preference to CO_2 from inorganic forms. It has b recognized for many years (Garrels and Dreyer, 1952) that consi ation of the chemistry of calcium and carbonate alone was adequate to explain the solubility relationships of calcium carbo in the environment. Neuberg, *et al.* (1957) gave evidence that teins and amino acids in sea water which appear to form carban carboxylic acids with CO_2 or bicarbonate ion would increase solubility of $CaCO_3$ and $Ca_3(PO_4)_2$ in sea water. Alekin and M cheva (1957) have reported that naturally occurring organic ac including amino acids, prevent precipitation of $CaCO_3$ in satura solutions. It is apparent that continuation of research along th lines will lead to a revision of the present concepts of the car dioxide system and of calcium carbonate precipitation and t

er significance will be attributed to the dissolved organic com-
ds in relation to these cycles.

e solubility of petroleum in water is increased by the presence
ganic acids of high molecular weight (Baker, 1958) and possibly
her compounds. If marine organic acids were adsorbed or oc-
d to sediments, these acids might play an essential role in the
ge and transportation of hydrocarbons. It has been demon-
ed that soluble organic matter adsorbed to sand grains changes
density so that they are more easily transported than other-
(Saunders, 1957). Likewise, organic matter adsorbed to clays
their ion-exchange capacity, ability to hold water, and general
dal behavior (Grim, 1953; Whitehouse, 1956).

us the molecular structure of various components of the soluble
nic fraction of sea water seems to be important to an under-
ling of the many different phenomena observed.

EXPERIMENTAL PROCEDURE

eparation of the Basic Experimental Solution. Water collected
ie surface from the Gulf of Mexico at the 100-fathom contour
placed in glass bottles, fertilized with nitrate and phosphate,
ed with $HC^{14}O_3$, and placed in light for 90 days. No sterilization
niques were employed. The sample was then placed in the dark
ne year to allow the organic material to decay. At the end of
time a relatively stable solution of C^{14}-labeled organic compounds
ined. The solution was acidified with HCl to pH 4.0 and aerated
emove all inorganic substances containing C^{14}. It was then neu-
zed to pH 7.0 and filtered through an HA-type millipore filter
pore size 0.45 μ) to remove the particulate material. This
me the basic stock solution used in evaluating methods of
rating dissolved organic materials contained in it; see below.
cording to Fox, *et al.* (1953), colloidal material from sea water
tained on 0.45 μ millipore filters. Thus, in this paper, reference
soluble" organic material implies material passing through a
μ filter. To obtain information concerning the size ranges of
materials involved, filtrates were also obtained by passing the
rimental solution through other pore-size filters; Table I shows
various size ranges and the approximate percentage of each.

^{4} *Counting.* All counting was done by means of a Nuclear Chi-
Model 182 A Scaler with D–47 gas flow end window Geiger tube.

Chromatography. Standard descending paper chromatogra techniques were employed, and in addition, electrochromatogra were prepared with the Microchemical Specialities Company elec chromatograph.

Carbon and Nitrogen Analyses. Total carbon was determined the wet combustion method described by Kay (1954), and nitro was determined by the micro-Kjeldahl procedure of Milton Waters (1955).

TABLE I. SIZE RANGE OF C^{14}-LABELED ORGANIC MATERIALS IN SEA WA

Size Range	*Type of Filter*	*°/₀ of Total*
15–1.5 μ	Fritted glass	6.3
1.5–0.45 μ	Fritted glass	37.5
0.45 μ–10 mμ	Millipore (Type HA)	6.2
Less than 10 mμ	Millipore (Type HA)	50.0

As a check on the efficiency of the five methods of isolation te for specific compounds, natural sea water, obtained from the s location in the Gulf of Mexico (see above), was prepared by filte it through a 0.45 μ millipore filter. Exact amounts of pure org compounds which are known to be biological metabolites added, and methods for isolation of these compounds were evalua

Description of Methods of Isolation.

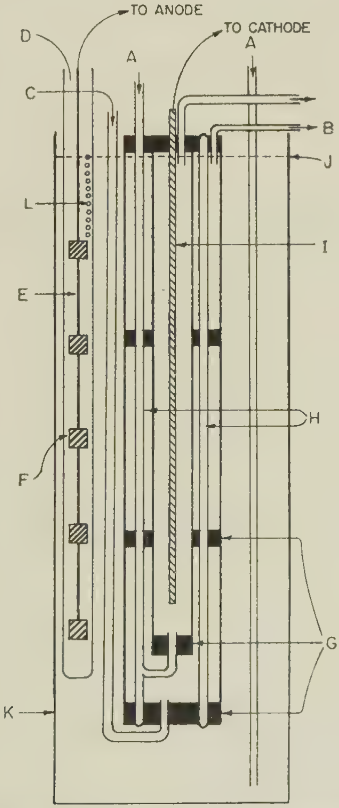
1 a. DIALYSIS. Cellulose acetate membranes (Visking Corporati with a reported pore size of 24 Å and a diameter of 3 cm, investigated to determine their effectiveness in separating org from inorganic compounds. The sea water was dialyzed by stan techniques against flowing tap water followed by distilled w

1 b. ELECTRODIALYSIS. Electrodialysis was investigated a method of isolating the organic and inorganic fraction of sea wat a cell of the type shown in Fig. 1. Cells of similar design contai 0.70–12.0 l of sea water have been constructed so that the w of greater density flows into the sea water compartment at bottom, where it is deionized and displaced by fresh incoming water. The supports are located so as to serve as a means of sepa ing the cathode membrane from the outside of the sea water membrane and of limiting diffusion between compartments. deionized sea water is then removed from the top of the sea w

The cathode is constructed of brass, of other metals which alkaline conditions, or of graphite. The anode is made of solid ite rod or plugs.

power supply having variable voltage between 1 and 120 volts a maximum amperage of 4 amps was used. Flushing rates maintained to give an effluent pH of less than 9.5.

. ELECTRODIALYSIS WITH ION-EXCHANGE MEMBRANES. Use of membranes, a currently important method for desalination of ater (Kirkham, 1956), was investigated. The membranes were



ure 1. Cell for electrodialysis by cellulose acetate membrane. A – fresh water input; esalted sea water output; C – sea water input; D – to aspirator; E – insulated con- r; F – carbon anode; G – rubber stoppers; H – support rods; I – brass or carbon ca- ; J – water level; K – glass container; L – perforated glass tube.

Rohm and Haas A–1 and C–1, and the cell was made of fabric
leucite. The electrodes were carbon blocks and the power su
delivered a varying amperage, depending on the salt content o
water and the conductivity of the cell. Sea water to which org
compounds in known amounts were added was placed in the
water cells and a potential of 70 volts was supplied across the m
branes for a period of 12 hours.

2. Adsorption. The following were used in columns for adsor
organic material: activated carbon, Granular Darco 4 × 12, sup
by Atlas Powder Co.; acid alumina, a powdered chromatogra
grade, No. Al–0109 T, supplied by Harshaw Scientific Co.; s
gel, 28–200 mesh, supplied by E. A. Sargent Co.; infusorial e
supplied by E. A. Sargent Co.; bentonite, supplied by Hars
Scientific Co.; and magnesium-oxide, reagent grade and, cal
carbonate, reagent grade, supplied by Mallinkrodt Chemical C

3. Ion Exchange. Samuelson (1954) reported the use of mi
bed ion-exchange resins for deionization of dilute organic solut
Amberlite resins (Rohm and Haas, IRC–50, IR 4–B, IRA–45, M
IR–120, and IR–400) and Dowex 1, 2, 3 and 50 resins (Dow Cl
ical Company) were used in these studies.

4. Solvent Extraction. Analytical grade, commercial solv
were used. In each case a 500 ml sample of sea water, adjuste
a suitable pH, was extracted five times with 25 ml of each solv
Recovery of the organic material from the solvent was accompli
(1) by direct evaporation or (2) by adding ether to the solv
extracting the organic material into an ammonium carbonate
ution, evaporating the water, and finally subliming the ammon
carbonate.

5. Coprecipitation. The pH of sea water was adjusted to
with ammonium hydroxide or other alkali. The resulting precip
of magnesium hydroxide contained much of the organic mate
The final precipitate was brought into solution for further isola
of the organic material.

A 0.1 M ferric chloride solution in sea water produces a f
hydroxide floc, with coprecipitation of organic material. L
concentrations act similarly but precipitation is slower. Solutic
the precipitate after separation from the supernatant followe

recipitation allows for purification of the organic material. Iron xtracted with isopropyl ether from 3 to 6 N HCl solution.

eduction of Solution Volume. A continuous feed flash-type evap- tor of 2 l volume obtained from Instrumentation Associates, York, was used. Also, a large evaporator was constructed from -foot tube-and-shell Corning pyrex glass heat exchanger which mounted at about 10° to the horizontal; the solution was al- ed to flow along the bottom surfaces of the tubes; upon flashing, vapors passed up the tubes toward the end of reduced pressure; affinate was then collected at the bottom. A pressure of ap- imately one pound was maintained in the evaporator and the et temperature was held at approximately 70° C. With recycling affinate, this system concentrated in excess of two gallons per r. With these evaporators the samples seldom reached a temper- re of over 60° C.

RESULTS AND DISCUSSION

ialysis, Electrodialysis, and Electrodialysis with Ion-Exchange mbranes. Dialysis and electrodialysis are established methods of arating dilute salt solutions from organic molecules. This tech- ue is used extensively in preparing samples for paper chromato- phic separation or in preparating column chromatograms. In se cases the concentration of organic material is relatively high proportion to the salt content. With sea water, the normal salt centration of about 35,000 ppm with an organic content in the ghborhood of 10 ppm results in a more difficult isolation.

n general, the efficiency of retention of this soluble organic frac- n by either dialysis or electrodialysis is dependent on the dimen- ns and arrangement of the cell components, on the initial and l salt concentrations, and on the inorganic and organic ions sent. Results of a study of the effect of concentration of salt on retention of glucose, methionine, and phenylalanine during or- ary dialysis are presented in Fig. 2. A salt concentration may be ected which will allow nearly complete recovery of some organic npounds, whereas at longer dialysis time (or with a lower salt centration) almost complete removal occurs.

n general, if dialysis is stopped at a salt content of not less than $/_{00}$, complete recovery of many of the small organic molecules is sible. If the resulting dialysate is then evaporated in a low-temperature flash evaporator until the salt content again becom 30–40 $^0/_{00}$, the sample can be redialyzed to a salt content of abo 1 $^0/_{00}$. This process may be continued with a large sample of s

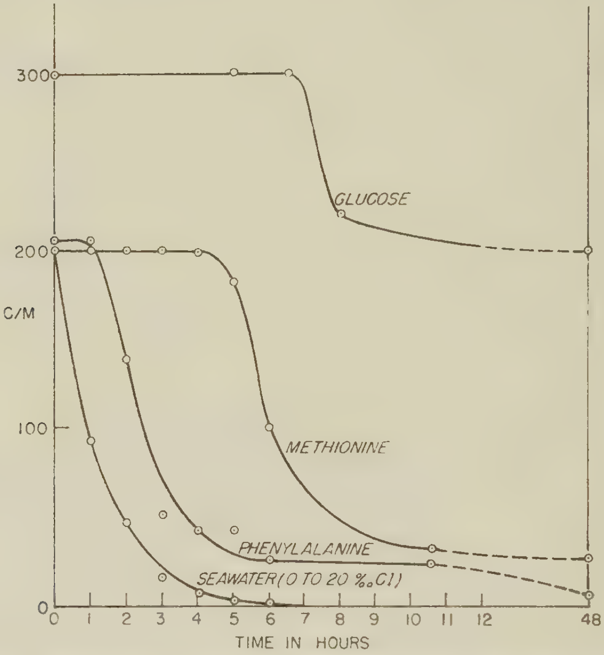


Figure 2. Concentration of certain organic compounds with time of dialysis.

water until the material in the final stage is predominantly organ with a low percentage of salt and a high retention of organic co pounds.

Retention of various organic molecules in dialysates of sea wat is shown in Table II. Ordinary dialysis over a period of six hou allows almost complete retention of glucose, sucrose, *DL* methi nine, *DL* histidine, thiamine, chlorophyll-A, penicillin, and t C^{14}-labeled organic matter of sea water. However, such compoun as ascorbic acid, alanine, and phenylalanine are poorly recover by this technique. The percent retention decreases substantially f small molecules if dialysis is continued as long as 15 hours. It noteworthy that the C^{14}-labeled organic matter of sea water completely retained under these dialysis conditions (Table III).

n preparing organic-carbon concentrates from sea water, using
anic membranes, leaching of the membrane may result in higher
n actual carbon values. It was found that between 10^{-6} and 10^{-4} g/l
arbon were obtained from new membranes by soaking them in
lled water. All membranes were therefore soaked and washed
re use.

arious ions in sea water do not dialyze in proportion to their
centrations. Solutions containing sulfate ion must have special
ment to reduce effectively concentrations of this ion. This may
accomplished by final dialysis against pure distilled water, but
process lowers the yield of organic constituents isolated. The
ate ion may also be removed by electrochromatography.

LE II. Retention of Organic Compounds by Cellulose Acetate Membranes During Dialysis and Electrodialysis

pounds	*Dialysis*		*Electrodialysis*		*Method of Analysis*
	*$^0/_0$ in 6 Hrs**	*$^0/_0$ in 15 Hrs***	*Per-cent*	*Cl ($^0/_{00}$)*	
ose	98	65	48	0.05	C^{14} counting
rose	98	68	53	0.05	C^{14} counting and anthrone
mnose	—	—	50	0.05	Anthrone†
finose	—	—	60	0.05	Anthrone
orbic acid	25	0	30††	0.05	Dinitrophenylhydrazine
ic acid	—	—	69	0.05	Dihydroxyacetone +
Alanine	5.0	0	5	0.03	C^{14} counting
Serine	—	—	20	0.03	Ninhydrin
Methionine	92.5	15	—	—	C^{14} counting
Histidine	90	0	—	—	Ninhydrin
Phenylalanine	20	10	5	0.25	C^{14} counting
Arginine	—	—	70	1.0	α naphthol△
amine	100	—	—	—	Spectrophotometric
amin B_{12}	—	—	100△△	0.1	*Lactobacillus leichmanii*
rophyll	100	100	0	0.03	Spectrophotometric
icillin	98	—	—	—	Total carbon
labeled organic tter of sea water	98	97	99(84)	1.0(0.03)	C^{14} counting

hloride content 0.5 $^0/_{00}$. – ** Chloride content 0.05 $^0/_{00}$. – † Morris, 1948. –
HPO$_3$ added. – + Hargreaves, *et al.*, 1951. – △ Koch and Hanke, 1943. –
HPO$_3$, NaHSO$_3$ + NaCN added. Mercuric chloride added in all cases to prevent
erial action.

Certain compounds (*e. g.*, vitamins B_{12} and C) and certain am acids (tyrosine, arginine, etc.) may be destroyed by dialysis electrodialysis procedures unless special precautions are taken. P treatment of water with certain chemicals (see Table II) preclu this decomposition in many cases.

When the above techniques are used, the volume of resulting di ysate is as great as or greater than the initial volume of sea wa sampled. To facilitate chemical analysis, the volume of solution m be reduced. Low-temperature flash evaporation was most suita Evaporation in these studies was carried out at 60° C, but in so cases, lower temperatures obtained by freeze-drying or desiccat may be desirable.

The technique of electrodialysis with ion-exchange membra may be expected to give results similar to electrodialysis in separ ing organic materials from salts. In addition, it has the advanta that many cells can be assembled with a single pair of electrod and the large equipment currently being used in the desalination saline water affords an opportunity to work with large volumes sea water in attempting separation of organic components.

By the end of the 12-hour experimental period in such an attem the chloride content was reduced to $0.03\ ^{0}/_{00}$. Under the conditi employed, recovery of organic compounds was about equal to t obtained in electrodialysis. It is believed that under controlled c ditions with respect to current, time and membrane arrangeme this technique has unrealized capabilities for the separation certain organic compounds.

Characteristics of Organic Concentrates Prepared by Electrodialy Natural sea water concentrates prepared by electrodialysis and fl evaporation had a yellowish-brown color and were soluble in alk were partially soluble in distilled water, methanol, pyridine, dimet sulfoxide, and were insoluble in acid, chloroform, ethyl eth petroleum ether, carbon disulfide, carbon tetrachloride and aceto

Ultraviolet and visible spectra showed no specific absorpt peaks for the material. Strong absorption noted in the ultravio region is thought to be due to inorganic salt. Preliminary infra spectra with the potassium bromide pellet technique were conclusive because of the high sulfate content of the concentra

Electrochromatography of the concentrate buffered at pH 7.0 3 mm Whatman paper showed at least three constituents wh

bited fluoresence in ultraviolet light. One remained at the origin;
second moved toward the positive side of the paper; and the
moved to the negative side. Customary spray tests for sugars
amino acids were negative.

scending-strip chromatography with various organic solvent
ures was compared with the electrochromatography technique.
constituents were apparent in phenol-acetic acid solvent, in
lutidine, and in butanol-pyridine-water (60–20–20). However,
fluorescent spots appeared when phenol-ammonium was used
e solvent.

nental analysis of the electrodialysis concentrate showed a
ratio of 13.8:1, absence of phosphorus, and a high content of
r as inorganic sulfate. Sulfate ion may be removed by electro-
matography, but it is a rather lengthy process. Precipitation by
entional methods results in the simultaneous precipitation of
nic materials.

evidence of protein resulted from ultracentrifugation of the
entrate. Free amino acids were not found, but after hydrolysis
acid, tests for amino acids were strongly positive, thus in-
ting the presence of peptides.

dsorption. Carbon appeared to be the most promising absorbent
he several tried for adsorption of organic materials from sea
er (Table IV). The liquid flow in carbon columns was also
er.

ecovery of added carbohydrates, amino acids, peptides, vita-
s, organic acids, and other organic compounds is shown in
le V. Carbohydrates were easily recovered by a method re-
ed by Whistler and Durso (1950) by elution with gradient con-
rations of ethanol. Dehydroascorbic or ascorbic acid was re-
red with 15 % ethanol elution. Amino acids were lost or de-
yed unless the columns were pretreated with hydrocyanic and
ic acids. The aromatic amino acids were strongly adsorbed on
on and were eluted with a number of solvents, such as phenol-
ic acid, isopropanol-water, or benzyl alcohol.

one were to proceed, it is expected that vitamin B_{12} could
e been removed with a 1:1 mixture of water and isopropanol
tes, *et al.*, 1950), and the antibiotics (streptomycin and peni-
) with methanolic formic acid (Kuehl, *et al.*, 1946, and Peck,
l., 1946).

TABLE III. EFFECT OF CURRENT AND TIME ON RETENTION OF ORGANIC MA
(Ret. = Retained)

Initial Current (ma)	*Voltage*	*Time*					
		8 Hours		*13 Hours*		*24 Hours*	
		Ret. (%)	*Cl* (%)	*Ret.* (%)	*Cl* (%)	*Ret.* (%)	*C*
1400*	15.0	14.0	0.5	14.0	0.5	14.0	
375	5.5	99.0	1.2	99.0	0.5	43.0	
250	2.5	99.0	0.9	99.0	0.5	97.0	
0	0	99.0	0.9	99.0	0.4	97.0	

* Precipitation of salts occurred immediately.

TABLE IV. SORPTION OF SOLUBLE ORGANIC MATERIAL FROM SEA WATER
30 × 1 CM ADSORPTION COLUMNS

Adsorbent	*Percent C^{14} Organic Material Adsorbed*	*Eluting Agent*	*Eluted* (%)
Activated carbon	100	Reflux with:	
		phenolacetic acid	62
		chloroform	trace
		acetone	trace
		methanol	trace
Acid alumina (Harshaw chromatographic grade)	65	NH_4OH	trace
Infusorial earth	65	—	—
Silica gel	15	—	—
Calcium carbonate	50	HCl	100
Magnesium oxide	50	HCl	100
Bentonite	65	—	—
Florex III	55	—	—

Effect of Activated Carbon on Organic Compounds. Activated
bon can cause aminolysis of amino acids as well as complete oxi
tion to CO_2, N_2O, and NH_3 (Wachtel and Cassidy, 1942). Th
oxidations can be largely prevented by the use of small quanti
of HCN. Carbon chromatography, which is used extensively
separation of carbohydrates, peptides, antibiotics, and fatty ac
is dependent on the uniformity of the carbon. Impurities which
constitute more or less active centers cause irreversible adsorpt
or trailing of part of the substances to be separated. The tende
to irreversible adsorption is greatly reduced by mixing the car
with some inert or weak adsorbent, such as diatomaceous earth

LE V. Sorption and Recovery of Added Organic Compounds from Sea Water on Granular Darco 4 × 12 Activated Carbon Columns

ound	*Pretreatment*	*Percent*		*Eluent*	*Analytical Method*
		Adsorption	*Recovery*		
nnose	H_2O	100	99	5 % Alcohol	Anthrone
se	H_2O	100	99	5 % Ethanol	Anthrone
se	H_2O	100	99	10 % Ethanol	Anthrone
nose	H_2O	100	98	15 % Ethanol	Anthrone
[illegible]	KCN, HAC	100	0	Phenolacetic acid	Ninhydrin
[illegible]	KCN, HAC	0	0	Phenolacetic acid	Ninhydrin
yl alanine	KCN, HAC	100	95	Phenolacetic acid	Ninhydrin
ne	H_2O	100	95	Phenolacetic acid	Ninhydrin
tophane	KCN, HAC	100	95	Phenolacetic acid	Ninhydrin
yl-DL-Serine	KCN, HAC	100	0	Phenolacetic acid	Total carbon
nine	H_2O	100	0	Phenol	Tatal carbon & absorption
bic acid	H_2O	100	98	15 % Ethanol	Dinitrophenyl hydrazine
ic acid	H_2O	100	0	Alcohols, Phenol	Total carbon
inic acid	H_2O	100	0	Phenol	Total carbon
n	H_2O	100	0	Phenol	Total carbon
rophyll	H_2O	100	0	Alcohols, Phenol	Spectrophotometric
nin B_{12}	H_2O	100	98	Isopropanol water	*Lactobacillus Leichmanii*
cillin	H_2O	100	98	Methanolicformic Acid	Total carbon
l radioactive ganic carbon sea water	H_2O	100	62.0	Reflux with liquid phenol	C^{14} counting

ition to pretreating it when recovery of such compounds as cides, certain amino acids, proteins, and fatty acids is desired.

haracteristics of Organic Concentrate Prepared by Carbon Adtion and Elution. The concentrate of natural sea water eluted the carbon column was yellowish-brown, and, like the elecialysis concentrate, it was partially soluble in water, methanol, pyridine but insoluble in acetone, ether, chloroform, or carbon achloride. A rather high ash content, apparently removed from carbon by the phenol, characterized the concentrate and made ies of its physical properties difficult.

he material was electrochromatogrammed in a series of different pH inorganic buffers with 3 mm filter paper. Four fluorescing c stituents appeared. Descending strip-paper chromatography w organic solvents yielded varying results. No separation occurre phenol-acetic acid solvent, but about six poorly-defined fluoresc spots appeared in phenol-NH_3 solvent. Four fluorescing spots w noted in pyridine-butanol-water (60–20–20) and in 2,4-lutidine- (80–20).

Ion Exchange Deionization. Several types and combinations ion-exchange resins were investigated in attempts to isolate C^{14}-labeled organic matter from the aged algae culture. W cation exchanger resins remove inorganic cations, they remove most none of the organic ions from sea water. On the other ha anion exchange resins remove both anions and organic materia a strong resin is used; if a weak resin is employed, approxima 40 % of the tagged organic material is removed. Combinations strong anion and cation exchange resins remove inorganic ions a large portion of the organic material. A strong cation and a w anion exchange resin combination was more effective in isola the C^{14}-labeled organic material from sea water. Combinations Dowex–50, IRA–45, and Dowex–3 were less useful than IRC and IR4–B, as shown in Table VI. Subsequently the Dowex– IR4–B combination was examined for its ability to isolate spe compounds from saline solutions. Known amounts of organic c pounds were added to sea water; the solutions were first pas over 30 × 1 cm columns of Dowex–50 maintained in the hydro form and then over IR4–B in the hydroxyl form. Both colu were washed with distilled water and all effluents were combi

TABLE VI. Recovery of Organic Compounds from Sea Water with Ion-Exchange Resins

Exchanger Type	*Percent C^{14} in Elutant*	*Percent Cl in El*
Dowex–50 (strong cation)	97.0	100
IRC–50 (weak cation)	95.0	100
Dowex–1 (strong anion)	0.0	0
Dowex–2 (strong anion)	0.0	0
Dowex–3 (weak anion)	60.0	0
Dowex–45 (weak anion)	60.0	0
IR4–B (weak anion)	90.0	0
IR–400 (strong anion)	0.0	0
MB–1 (IR–120 + IR–400)	25.0	0

vaporated under vacuum at 60° C. Analyses of the specific ic compounds are shown in Table VII.

VII. EFFICIENCY OF DOWEX–50 CATION EXCHANGE RESIN AND IR4–B EXCHANGE RESIN IN SEPARATING KNOWN ORGANIC FROM INORGANIC COMPOUNDS OF SEA WATER

ganic Compound	*Through* IRC–50 (%)	*Through IR4–B* (%)	*Method of Analysis*
Raffinose	98	97	Anthrone
Rhamnose	98	96	Anthrone
Xylose	95	93	Anthrone
Glucose	95	93	C^{14} tagged
Sucrose	97	95	Anthrone
Alanine	99	98	C^{14} counting
Methionine	99	98	C^{14} counting
Phenylalanine	98	97	C^{14} counting
Thiamine	99	98	Total carbon and Ultraviolet absorption

e data in Table VI indicate that organic material of the aged culture consisted predominantly of negative ions, of which are weakly negative and 40 % are strongly negative. The gly negative ions are probably derived from organic acids, ll be shown later.

ce ion-exchange resins are insoluble acids or bases, a series of ions could be brought about by their action on organic com- ds. Carbohydrates are especially susceptible to strong base s (Samuelson, 1954). Strong cation and weak anion exchange s were chosen in this study, thus minimizing the possible de- tion of the organic material present.

sadvantages in the use of ion-exchange resins: high values for ic matter are obtained in the controls unless extreme care ime are taken in washing the resins; large resin quantities are sary to desalt a sufficiently large sample of sea water; volume tracted liquid is at least double the original sample.

-exchange resins probably have their greatest value in final ations of partially desalted organic concentrates prepared by methods. For example, the sea water organic concentrate t be passed over a small column of Dowex–50 and then over -45. Carbohydrate materials would go through both columns,

nitrogenous bases would remain on the first column, and or
acids would remain on the second column. The organic ma
could then be recovered by eluting the first column with d
HCl and the second with NH_4OH.

Solvent Extraction. Many common solvents for liquid-liqui
traction of soluble organic compounds from sea water were in
igated. The C^{14} activity of both the solvent and the water p
was determined by drying an acidified portion of each phase
by measuring the C^{14} activity. Table VIII presents the data obt

TABLE VIII. THE EFFICIENCY OF SELECTED SOLVENTS FOR LIQUID-LIQU
TRACTION OF C^{14}-LABELED ORGANIC COMPOUNDS FROM SEA WATER

Solvent	*Initial pH of Sea Water*	*Organic Material in Solvent Phase (approx. %)*
Ethyl ether	5.0	5.0
Hexane	5.0	5.0
N-ethyl-n-butylamine	8.2	5.0
Chloroform	5.0	5.0
Carbon tetrachloride	5.0	5.0
Carbon disulfide	5.0	5.0
Toluene	5.0	11.0
Aniline	8.2	12.0
n-butanol	3.0	13.0
Isobutanol	3.0	13.0
Phenyl ethyl alcohol	5.0	16.7
Hexyl carbitol	5.0	17.0
Phenyl carbitol	5.0	18.2
2-methyl 5-ethyl pyridine	8.2	22.0
2,6-lutidine	8.2	32.0
Phenol	5.0	68.0
	8.2	68.0
Ethyl acetate	2.0	40.0
	8.2	20.0
Amyl acetate	2.0	10.0
Benzyl alcohol	2.0	68.0
	8.0	68.0

with various solvents. Phenol, benzyl alcohol, ethyl acetate,
2,6-lutidine were the most promising solvents from the stand
of quantities of radioactive organic material extracted. Data

f study of the types of biological compounds extractable by four solvents are presented in Table IX.

IX. Extractibility of Specific Organic Compounds from Sea Water y Phenol, Ethyl Acetate, 2,6-Lutidine and Benzyl Alcohol
(Ext. = Extractability)

mpound	*Method of Determination*	*Phenol*		*Ethyl Acetate*		*2,6-Lutidine*		*Benzyl Alcohol*	
		Ext.	*pH*	*Ext.*	*pH*	*Ext.*	*pH*	*Ext.*	*pH*
	C^{14} counting	*	5.0	*	3.0	*	8.2	—	—
lanine	C^{14} counting	++	5.0	++	3.0	+	8.2	+	5.0
ine	C^{14} counting	+	5.0	+	3.0	+	8.2	*	5.0
	C^{14} counting	*	5.0	+	3.0	++	8.2	+	5.0
	Anthrone	*	5.0	—	—	—	—	+	5.0
ose	Anthrone	+	5.0	—	—	—	—	+	5.0
se	Anthrone	*	5.0	—	—	—	—	—	—
roascorbic acid	Dinitro phenyhydrazine	*	5.0	*	3.0	—	—	—	—
ne	Total carbon	++	5.0	—	—	—	—	++	5.0
n B_{12}△		++	5.0	—	—	—	—	+	5.0
ic acid	Total carbon	++	5.0	—	—	—	—	++	5.0
dl-alanine	Total carbon	*	5.0	—	—	—	—	—	—
dl-phenylalanine	Total carbon	*	5.0	—	—	—	—	—	—
nucleic acid	Total carbon	*	5.0	—	—	—	—	*	5.0
phyll	Spectrophotometric	++	5.0	*	8.0	—	—	++	5.0
eled organic erial	C^{14} counting	++	5.0	+	—	+	—	++	5.0

early Quantitative Extraction (50–100 %); + Partial Extraction (10–50 %); Negligible Extraction (0–10 %). △ (Cowey, 1956).

aracteristics of Marine Organic Compounds Isolated by Liquid-d Extraction.

Ethyl Acetate Extract. Records were made of visible, ultra- and infrared spectra of an ethyl-acetate extract of 5 gallons ered sea water recently collected. The visible spectra showed aks, but strong absorption occurred in the ultraviolet region. nfrared spectrum showed several peaks (3140 – 2800 cm^{-1} (CH), (C = 0), 1450 (CH_2), 1410 (C – O), 1280 (C – O) and 745 ($(CH_2)X$), ating a mixture of weakly ionized acids, possibly including acids. Ethyl-acetate extracts of sea water from which the organic matter had been removed in carbon columns were us controls.

Each extract and its corresponding control were electrochrom grammed, employing a series of inorganic buffers ranging in from 2.0 to 8.6 on both 3-mm Watman and Schleicher SS598 matography paper. Voltages of 900 and currents of 5–10 ma commonly used. Two spots which fluoresced strongly in ultrav light were easily separated by this method. One spot remained the origin and the other moved rapidly toward the negative elect

This extract was also chromatogrammed on strips of 3-mm matography paper in a series of organic solvents with nearly same results. In basic solvents such as butanol-pyridine- (60–20–20) and 2,6-lutidine-water (80–20), the spot remaine the origin; *i. e.*, no separation occurred. In butanol-ethanol- (60–20–20) two spots appeared, but the separation was not as as that in the electrochromatography technique. It may be t tively concluded that two types of acids were present. The e acetate extract had an average molecular weight of 403, determ by means of the ebullioscopic technique (Bonner, *et al.*, 1958

b. PHENOL EXTRACT. Extracts of sea water with phenol conta a relatively high ash content; hence, many of the usual phy tests were omitted. The visible, ultraviolet, and infrared sp resembled those of the ethyl-acetate extract. However, one ex of sufficient purity and concentration showed an ultraviolet c which corresponded to that of thiamine. Weakly ionized acids strongly indicated by infrared analysis.

Electrochromatography of the phenol extract showed fluorescing spots in contrast to the two found with the ethyl-ac extract. In descending-strip chromatography in butanol-eth water (60–20–20), five fluorescing spots were detected; in ph ammonia (trace NH_3), four fluorescing spots were detected.

Coprecipitation. When the pH of sea water is increased to all magnesium and calcium salts and a large percentage of th ganic matter are precipitated. According to our results, 79 the C^{14}-tagged organic matter of the aged algae culture is pre tated with these salts. The dried precipitate contains 1.2 $^0/_0$ ca whereas the original sea water contained 5 mg/l or 0.0005 $^0/_0$; the carbon is concentrated by a factor of 2,000. Concentratio the soluble organic matter is increased even more by simply ac

M $FeCl_3$ to sea water at its normal pH of 7.6 to 8.2. Approxi-
ely 95 ${}^{0}/_{0}$ of the soluble organic matter is precipitated with
H)$_3$, as shown by results with C^{14}-tagged water. With $Fe(OH)_3$
soluble organic matter of natural sea water was concentrated
factor of 10,000. Either precipitate may be decanted and re-
lved in acid; then the inorganic salts may be removed by re-
pitation, by solvent extraction of the organic material, or by
ption of the inorganic ions on ion-exchange columns.
ects of precipitation with alkali or ferric chloride on soluble
nic compounds are not known. It is believed that this method
distinct possibilities in isolating large quantities of the total
rum of soluble organic compounds from marine waters.

CONCLUSIONS

antitative isolation of soluble organic compounds from sea water
out alteration of one or more constituents is difficult for four
ons: (1) many compounds are easily destroyed by bacterial
on; (2) the ratio of inorganic to organic material in sea water
tremely high; (3) destruction by heat or slight change in chem-
conditions is difficult to prevent in the case of many compounds
iological origin; and, (4) organic matter readily adsorbs to sur-
s where it becomes difficult to desorb. In the final analysis,
factory isolation requires great care if definite conclusions are
e drawn concerning the nature and quantity of the organic
tituents present.

our possible ways are indicated for the isolation of at least a
ion of the soluble organic constituents of the oceans: (1) dial-
or electrodialysis, (2) column adsorption and elution, (3) sol-
extraction, and (4) coprecipitation. Ion-exchange deionization
d be considered a fifth method, but because of the high value
rganic matter in the control and because of the large volumes
esin necessary, it is usable only in the final stages of removal
races of inorganic ions and in separating the classes of organic
erial. Table X summarizes the efficiency of each method for
oval of soluble organic matter and points out the advantages
disadvantages of each technique.

he coprecipitation method holds tremendous possibilities, since
moves practically all of the organic species from solution. How-

TABLE X. SUMMARY OF EFFICIENCY OF VARIOUS METHODS FOR ISOLATIO ORGANIC MATERIAL FROM SEA WATER

Method	*Total Organic Matter Isolated* (%)	*Advantages*	*Disadvantages*
Electrodialysis with cellulose membranes	97	Ideal for large molecules or colloidal micelles.	Inorganic sulfates n moved. Large vol of water must be orated at a low perature.
Carbon adsorption and elution with phenol	100 adsorbed 62 removed with phenol	All of organic constituents adsorbed.	Carbon must be refl with phenol, whic moves inorganic in ities from carbon.
Coprecipitation with $FeCl_3$	100	All of organic constituents conc. by a factor of 10,000 in one simple operation.	$Fe(OH)_3$ must be rated from organic tion.
Solvent extraction		Quick and simple to prepare an organic concentrate without altering organic compounds materially.	Any one solvent rates only a fra of the organic m
A. Phenol	65		
B. Ethyl acetate	40		
C. 2,6-lutidine	32		
Ion Exchange	65	No particular advantage.	Too large an organic l is obtained. Imp cally large volum resin are necessa prepare a sample. ge amounts of l must be evaporat obtain the organic centrate.

ever, there remains the secondary problem of separation of f ion or other coprecipitating ions from the organic matter.

Column adsorption, especially with pretreated activated car is effective in the removal of organic materials from sea water, only part of the organic fraction (carbohydrates and some pro aceous material) can be readily eluted.

Dialysis and electrodialysis are useful methods, but they mus used with care to avoid precipitation or destruction of the pounds. Most membranes which retain a reasonable percentag small organic compounds will also retain inorganic sulfates, w can, however, be removed by electrochromatography. These t

es necessitate evaporation of large quantities of water at a low
perature, which is inconvenient. Nevertheless, for certain pur-
s, such as isolating large molecules or small colloidal micelles,
ysis or electrodialysis is probably the most effective method
stigated.

r ease and speed in obtaining an organic concentrate, the sol-
extraction method is most propitious. It is also felt that the
hod causes less damage to the organic compounds extracted.
ingle solvent removes all compounds, and some compounds may
e extracted effectively by any solvent. Ethyl-acetate, phenol,
tidine, and benzyl alcohol appear to be quite useful, especially
ey are of high purity.

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OBSERVATIONS ON INSHORE PLANKTON COLLECTED DUR
SUMMER 1957 AT POINT BARROW, ALASKA[1]

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ABSTRACT

Analyses of 34 net tows, collected July 16 to August 16, 1957 to depths of
66 m, were concerned mainly with the microplankton. The concentration of pla
varied greatly while the composition remained quite uniform. *Acartia longi*
Oithona similis and *Pseudocalanus minutus* were the most abundant copepods.
species of Calanoida recorded include *Acartia clausi*, especially in Nuwuk
Calanus finmarchicus; *C. hyperboreus*; *Centropages mcmurrichi*; *Epilabidocera*
phitrites; *Eurytemora herdmani*; and *Tortanus discaudatus*. The presence of n
and early copepodid stages of *E. amphitrites* and *T. discaudatus* are of inter
demonstrating some reproduction by these more southerly forms on the
coast and in pointing to a tenuous faunal connection of the east and west
populations of *T. discaudatus*.

The macroplankton, especially *Limacina helicina*, *Clione limicina* and *Thysa*
raschii, were most conspicuous following heavy on-shore winds bringing in i

The temporary zooplankton consisted mainly of pelecypod, gastropod, an
barnacle, echinoderm and brachyuran larvae. Clypeasteroid plutei were com
although benthic adults have not been reported from the immediate area.
larvae were rare.

Results from culturing of copepods up to August 15 show that single iso
females of *Cyclops* from Imikpuk Lake are capable of producing a minimu
three successive broods without additional fertilization over the period.

INTRODUCTION

A brief study was made of the general character of inshore ma
plankton in the Point Barrow area of Alaska from July 16 to Au
16, 1957. Although ice conditions permitted sampling only wi
five miles of shore, this study supplements studies of offshore pl

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from collections made by the ice breaker USS BURTON ISLAND
vo extensive cruises in the summers of 1950 and 1951 (John-
1956). Previously the inshore plankton of Alaskan seas along
Arctic coast of North America had been studied to some
t in a preliminary survey by the Canadian Arctic Expedition
18 (Willey, 1920). The early marine investigations of the Arctic
rch Laboratory, concerned mainly with the benthic fauna,
ded primarily gross analyses of only the large plankton forms
Ginitie, 1955).

e present report concerns particularly the microplankton,
ally some of the copepoda and larvae of benthic invertebrates.
e collections comprise: 25 net tows taken just off the Arctic
arch Laboratory, a few miles west of Point Barrow and sea-
to about four miles, depending upon ice conditions; five tows
Eluitkak Pass just east of Point Barrow; and four tows from
uk Pond. This somewhat brackish pond, about 250 m in length
about 6 m deep, is isolated from the sea by a gravel and perma-
barrier near the Point. The sampling was done with both fine
20 mesh) and medium (Nos. 4 and 8 mesh) bolting silk nets
d horizontally at the surface or obliquely and vertically from
hs up to about 30 m.

RESULTS

e characteristic percentage composition of plankton, as shown
everal typical hauls, is given in Table I.

PEPOD PLANKTON. The concentration of plankton varied greatly,
the composition remained quite uniform, with but few genera
species. Usually some harpacticoids occurred but these were
identified or counted. Two species of copepods, *Acartia longi-*
s (Lilljeborg) and *Oithona similis* Claus were numerically the
inant forms (Table I). Nauplii of these genera were also the
numerous observed. It was expected that *Acartia clausi* Gies-
ht, a more strongly neritic species than other Acartias, would
ore abundant than it was, but a careful examination of 25 or
adult females from each tow showed only a few specimens,
pt in collections from Nuwuk Pond, where it was the only
tia found. The abundance of *A. longiremis* is of special interest
ght of its small penetration in numbers and area into the Beau-
Sea, as shown by the USS BURTON ISLAND collections, in which

no *Acartia* occurred in the Beaufort Sea except as a diminis
extension from the Chukchi Sea population and as scattered i
viduals near shore.

Among the copepods occurring only rarely or in small num
in the collections are the following:

Calanus finmarchicus (Gunnerus), a cosmopolitan species,
usually represented by only scattered specimens, nearly all in e
copepodid stages. Some large *Calanus* nauplii, probably this spe
occurred commonly. The scarcity of *Calanus* species and the
sence of other forms such as *Metridia longa* (Lubbock) and *M*
calanus pygmaeus (G. O. Sars), all of which are common offs
further demonstrates that in this area as elsewhere there is a
distinction between inshore and offshore pelagic environment,
favoring its characteristic fauna. However, offshore forms do p
trate close to the coast when the water is deep, as shown b
oblique tow with a 1-meter net (No. 30 mesh gritgauze with a
tures of approximately 0.65 mm) from the bottom at 66 m ab
the Ivik on August 8 about four miles from shore. In this to
Calanus finmarchicus (including adult females and copepodids
IV and V) and one *Calanus hyperboreus* Krøyer were taken. A
face tow of undetermined length taken at the same station wi
$^1/_2$-meter net contained many neritic forms (Table I).

Centropages mcmurrichi Willey 1920 was consistently present,
in only small numbers. There is some doubt as to the proper n
of this species. In describing the species, Willey included no fig
But reference to the figures given by McMurrich (1916), who li
the species with some doubt as *Centropages hamatus* (Lilljeb
and to the figures by Mori (1937) for *Centropages abdominalis*
(1913), indicates that *mcmurrichi* and *abdominalis* are synonym
Should further study of Sato's description show this to be so
species name must be used.

Epilabidocera amphitrites (McMurrich) was found in five t
one of which was in Eluitkak Pass. Usually the species was f
only in the readily recognizable nauplius stage (Johnson, 1
But several adult females and males were also captured in a $^1/_2$-m
net on August 8 about four miles offshore. This species, origin
described from the west coast of Vancouver Island, is at t
abundant in Puget Sound and is reported also from San Fran
Bay (Esterly, 1924). It was found in small numbers in neritic wa
of the Bering Sea and off Cape Lisbourn, Alaska. In 1950 it

found near Point Barrow, but the present record is its farthest
ward known penetration along the Arctic coast. Its absence
the east coast of North America suggests that, even though
capable of penetrating into the Arctic Ocean to a distance just
of Point Barrow and is even able to reproduce to some degree
e, still it has not been able to negotiate the remainder of the
ic coast to become established as an endemic form of the West
tic. In this respect it contrasts sharply with *Tortanus discau-*

rytemora herdmani Thompson and Scott is a small neritic and
kish water species. In the coastal collections it usually occurred
ely as scattered individuals. However, in one surface haul three
our miles offshore it was common, the males outnumbering the
ales by about 30 to 1. Nauplii were also present in small numbers.
Nuwuk Pond this species was present in large numbers, being
erically the dominant crustacean in the pond, where it was
vely reproducing. In contrast to the coastal collections, about
$/_0$ of the adults were females, most of which carried egg sacs.
developmental stages were present, nauplii and copepodids
ng especially numerous.

Nuwuk Pond has been studied previously by Mohr (1953) who
reported a salinity of 24.5 $^0/_{00}$ for July 1952. How constant this
nity remains is apparently not known, but the pond is said to
reached at times by ocean waves during autumnal storms. In
dying the life of the pond, Mohr was concerned with only the
ger animals, *Mysis relicta* Loven, two gammaridean amphipods
l an enchytraeid worm. To the crustaceans inhabiting the pond
now be added the copepods *Eurytemora herdmani*, *E. canadensis*
l *Acartia clausi*, and, among unidentified copepods, a cyclopoid
l an harpacticoid. Ostracods and tintinnids also occurred. The
y living vegetation found by Mohr was an algal film on the gravel
shallow water. The present study shows a good crop of phyto-
nkton consisting of a small species of the diatom *Chaetoceras*.
e extent to which the composition of this fauna and flora changes
y depend upon the extent of renewal of water from the sea to-
her with its load of euryhaline organisms.

Pseudocalanus minutus (Krøyer) is the third most abundant cope-
l encountered at coastal stations, where it was present in all
nples. The numbers counted are probably minimal because exact
ntification is difficult, especially in subadult stages, so it is likely

TABLE I. PERCENTAGE COMPOSITION OF TYPICAL INSHORE MICROPLANKTO
POINT BARROW, ALASKA, JULY AND AUGUST 1957

Location	*Eluitkak Pass*	*Off Arctic Research Laboratory*				
Date	*July 22*	*July 24*	*Aug. 1*	*Aug. 2*	*Aug. 8*	*Aug. 14*
Type of Net and Haul	*40 cm* *# 8 mesh* *surface*	*40 cm* *# 8 mesh* *surface*	*40 cm* *# 8 mesh* *surface*	*40 cm* *# 8 mesh* *oblique* *30–0m.*	*1/2-m* *# 4 mesh* *surface*	*1/2-m* *# 4 mesh* *oblique* *10–0 m.*
Acartia clausi	+		+			+
Acartia longiremis	32.0	53.2	13.8	23.2	51.0	4.8
Calanus finmarchicus	+	+	+	+		
Centropages mcmurrichi	0.4	0.6	0.3	0.5	0.2	+
Epilabidocera amphitrites						
nauplii	+			+	+	
copepodid				+	+	
adult					+	
Eurytemora herdmani					0.4	+
Oithona similis	15.6	13.8	28.4	24.8	28.0	21.9
Pseudocalanus minutus	+	1.9	4.3	2.0	3.0	+
Tortanus discaudatus						
nauplii		+				
copepodid II		+				
copepodid IV			+			
adult		+			+	
Copepod nauplii	15.2	10.6	19.1	17.7	4.0	6.1
Copepod spp.	17.2	3.3	16.1	8.5	0.4	1.2
Amphipods (Gammaridean)	+	+	+	+		
Barnacle nauplii		0.6	0.5	7.5	5.0	29.0
– cyprids	+	+	+	1.9	+	+
Brachyuran zoea	+		+	+	+	+
Macruran larvae		+				
Evadne		+				+
Podon	0.4	0.7	0.5		+	7.3
Gastropod larvae	2.5	3.2	4.3	3.9	1.0	5.1
Lamellibranch larvae	2.5	7.4	1.5	2.7	3.0	20.8
Clione limacina	0.1	0.1	+	+		+
Limacina helicina	0.1	+	+	0.2		+

+ Present singly or in small numbers.

TABLE I (continued).

n	Eluitkak Pass	Off Arctic Research Laboratory					Av. % Copepods Only
	July 22	July 24	Aug. 1	Aug. 2	Aug. 8	Aug. 14	
Net	40 cm	40 cm	40 cm	40 cm	$^1/_2$-m	$^1/_2$-m	
aul	# 8 mesh	# 8 mesh	# 8 mesh	#8 mesh	# 4 mesh	# 4 mesh	
	surface	surface	surface	oblique 30–0 m.	surface	oblique 10–0 m.	
larvae	8.2	0.9	9.3	4.1	0.4	2.0	
	0.8	3.4	+	0.8		+	
	3.3	0.3	1.5	+	3.0	1.4	
ria larvae				+			
plutei	1.6	+	+	2.2	0.4	0.5	
lutei		+	0.5	0.2			
autes larva						+	
ura					+		

ent singly or in small numbers.

ter preponderantly into enumeration of unidentified copepods. widespread in Arctic and sub-Arctic seas.

tanus discaudatus (Thompson and Scott) was present in five two of which were in Eluitkak Pass. In the August 8 tow off rctic Research Laboratory, about 30 adult males were caught, the other tows combined, only one nauplius, three copepodids II, IV) and one adult male were found. No floating egg cases observed. In 1951, some egg cases were found and one specimen aken at each of three adjacent stations off the Coleville River. these data it seems clear that *Tortanus discaudatus* is able to duce to a limited extent in the region of Point Barrow and me distance to the east.

is species, inhabiting both the east and west coasts of Canada he United States, is often abundant in coastal waters. On the coast it ranges southward to La Jolla, California. Few plankton vations are available along the Arctic coast, but doubtless is or has been at times a more or less tenuous connection be- the east and west coast populations. How complete or per- t this connection may be is an interesting question. The trans- with water currents appears to be from west to east along the of the Beaufort Sea. With respect to its northern limits on the east coast, the species is not mentioned by Fontaine (195 three summer surveys of copepods in Ungava Bay. Willey (has reported it in only small numbers from Richmond Gulf James Bay in Hudson Bay.

Miscellaneous Plankton. Conspicuous in the macroplan were *Limacina helicina* and *Clione limacina* which, while us occurring only as scattered individuals in the tows, were on occasion blown in with the ice and formed extensive windrow the beach. Also among the zooplankton stranded on the beach considerable numbers of the euphausiid *Thysanoessa raschii* (M. and ctenophores, probably *Mertensia*, which was numerou Eluitkak Pass on July 16. At this time the copepod plankt Eluitkak Pass was unusually sparse, likely as a result of pred by the ctenophores. Young *Sagitta* (4 to 10 mm) occurred regu but never in abundance.

An important part of the neritic population was the temp plankton found at all stations out to the edge of the ice. This p ton consisted mainly of larvae of bottom-living inverteb especially larval pelecypods, gastropods, annelids, barnacles echinoderms together with a good number of decapod larvae, ticularly brachyuran zoea. A small number of ascidian tadpole l were observed, and a single specimen of the bryozoan cyphon larva was caught. The advanced stage of growth of many o invertebrate larvae indicates that reproduction was well under before the survey was begun. Fish larvae were exceedingly ra

The echinoderm larvae that occurred most commonly were c asteroid plutei. These were similar if not identical to the lar the sand dollar *Dendraster excentricus* (Eschscholtz), judging the structure of the calcareous rods supporting the arms (Jo and Johnson, 1950). The postoral rods are fenestrated in ch teristic clypeasteroid fashion (Mortensen, 1921). The presen these larvae is interesting, in part because, in the benthic s of the area, MacGinitie (1955) found only one echinoid, *i. e.*, *S gylocentrotus drobachiensis*, a species with a recognizably diff larva. The present observation would indicate that a conside sand dollar population may be expected in some adjacent s bottom environment that has not been examined. It is pro that among the as yet unidentified larvae there may still be o that are indexes to unreported local adults or to transport of l the more southernly Alaskan coastal areas along the Bering Chukchi seas.

e occurrence of so many planktonic larvae of the benthos is of significance in that it implies sub-Arctic conditions at Point ow with respect to the life history of many of the invertebrates; ver, an analysis has not been made of the precentage of bot- nvertebrates that have a life cycle involving pelagic larvae. would be an important consideration. Specific or generic iden- ion of most larvae was not attempted, but several types of e indicating taxonomic differences were noted. In the high of East Greenland only 5 $^0/_0$ of the bottom invertebrates ce pelagic larvae, but these few may be quantitatively the common (Thorson, 1950). From this brief study it was also ssible to arrive at any conclusion as to whether the planktonic was a relatively short one compared with that of the same or ed species in more temperate waters. Here again a flow of r mainly from the Alaskan coastal area of the Chukchi Sea er than through the Beaufort Sea must have an ameliorating t that is favorable to planktotrophic pelagic larvae.

s supplementary work, especially when ice conditions were un- rable in the sea, samples of gravid females of *Eurytemora herd- i* from Nuwuk Pond and of a cyclopoid from Imikpuk Lake h water) were isolated in culture dishes. These cultures were at the laboratory in an unheated room where temperatures ained near that of the natural environment. No food was added r than detrital material from the habitats. This may have been equate food for egg production and for growth of the developing es. The adult specimens, however, survived in most instances two to four weeks, when the experiments were terminated. objective in these experiments was to gain some preliminary rmation relative to the fecundity of Arctic copepods.

esults from the culturing of these copepods up to August 15 that single isolated females of *Cyclops* from Imikpuk Lake are ble of producing at least three successive broods of active nau- without additional fertilization during the period. The resulting ae of these broods grew slowly and survived rarely beyond the nd naupliar stage. However, in one culture they reached the copepodid stage in a minimum of 15 days after the eggs hatched July 24. By August 15, when the animals were preserved, they all reached the second copepodid stage.

The *Eurytemora herdmani* did not perform as well as the al mentioned specimens. Each female produced only one broo captivity but, as with *Cyclops*, it is not possible to know how m if any, broods had been produced before isolation. Most of the la died within ten days, but a few reached the second naupliar st

A study of the external morphology of the naupliar stage *Eurytemora* from plankton collections made in the lagoon wil published elsewhere.

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THE ANNUAL CYCLE OF PHOSPHORUS AND NITROGEN NEW ENGLAND COASTAL WATERS

BY

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ABSTRACT

Distributions of phosphorus and nitrogen in New England coastal wat various times of year are described. In surface waters the nitrate-nitrogen co is sometimes completely exhausted, even though small concentrations (0.2–0.5μ of phosphorus are always available. The ratio of concentrations by atoms, varies in surface waters from maximum values of about 10:1 to values approa zero as the nitrate is exhausted. However, the ratio of change, $\Delta N:\Delta P$, is ap imately 15:1 except during summer months when it decreases. During sur vertical mixing supplies nitrogen and phosphorus to the euphotic zone at l ratios than the ratios of concentration in the euphotic zone. In deep offshore the N:P ratio is about 12.5:1, and no significant seasonal variation in eithe phosphorus or nitrate concentration at the oxygen minimum-nutrient max layer could be detected.

INTRODUCTION

Phosphorus and nitrogen concentrations in surface waters o sea decrease as a result of utilization by phytoplankton but replenished by decomposition of organic matter *in situ* an mixing, which brings supplies back to the surface from ri deeper waters. The concentration of these two elements chan a correlated way. Harvey (1926) commented upon the remark fact that during the spring outburst of phytoplankton in the En Channel both nitrogen and phosphorus were reduced simultane to negligible concentrations. Redfield (1934) showed that this servation of Harvey's was generally applicable to various oc bodies of water and that the ratio of change of concentration

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r in all of the waters studied. When the phosphorus concen-
n values are corrected for salt error, as suggested by Cooper
, these elements vary in a ratio of 15 atoms of nitrogen to
f phosphorus. As shown by Redfield (1934) and Fleming
the ratio in which the elements vary in sea water is closely
rable to the concentration found within living marine
sms.

n the ratio of concentrations in a single sample of water is
ed, it is frequently found that this has a different value
he 15:1 ratio of change. Cooper (1937, 1938) termed the dif-
between the 15:1 ratio and the observed ratio the anomaly
N:P ratio; and he pointed out also that this anomaly is
st in confined seas such as the Mediterranean. Phifer and
pson (1937) showed that this ratio had a mean annual value
Juan Channel of 12.7 but that it varied throughout the year
11.9 to 13.6. Even more extreme values for the N:P ratio
found by Riley and Conover (1956) in Long Island Sound.
, on a seasonal cycle, the ratio varied from nearly zero to 8:1.
xtremely low values reflect the fact that phytoplankton were
o remove practically all of the nitrogen from the water even
h there was a small residual concentration of phosphorus
t 0.5 μg-at/l).

r the last two years, during investigations in coastal waters
ew England at stations shown in Fig. 1, concentrations of
en and phosphorus have been measured on each cruise. Even
se exposed coastal waters the ratio of concentrations in sur-
waters is low, and, as in Long Island Sound, values fluctuate
near zero in the summertime to 5–10 in midwinter. In spite
se low ratios of *concentration*, the ratio of *change* of nitrogen
hosphorus in the surface waters corresponds closely to a ratio
:1, excepting changes in surface waters in summertime.

METHODS

cruises which have been made to the area indicated in Fig. 1
ted in Table I. Aliquots of samples taken from various depths
rozen immediately in 500 ml plastic bottles at a temperature
ut −15° C. Duplicate analyses of fresh samples at sea and of
samples have confirmed the fact that frozen samples give
ctory results for inorganic phosphorus, nitrate, nitrite and

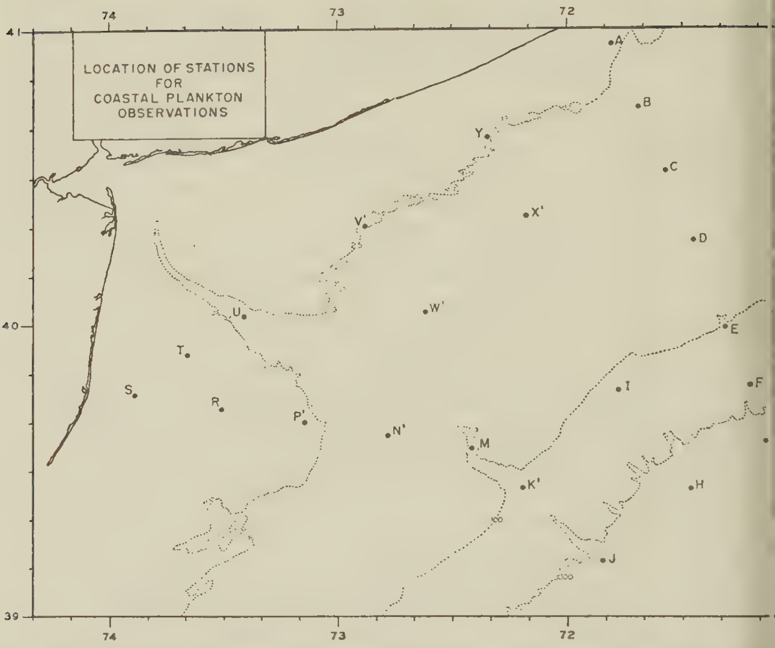


Figure 1. Location of stations occupied during coastal cruises, September 1956

ammonia nitrogen and silicate analyses for periods of at le month of frozen storage.

The method for inorganic phosphorus determination has described by Wattenberg (1937), Robinson and Thompson (and Wooster and Rakestraw (1951). The color developed measured in a photoelectric colorimeter (Ford, 1950), using light filter (Corning 2408) and absorption cells of 29 and 8 cm path for concentrations of less than 1.0 and more than 1.0 μg-a respectively. The reproducibility of the method was discusse Ketchum, *et al.* (1955), who have given analytical variatio ±7 $^0/_0$ for the low concentrations in the 29 cm tube and of for the higher concentrations in the 8 cm tube. Total phosp was determined by the method described by Harvey (194 modified by Ketchum, *et al.* (1955).

The nitrate concentration was determined by hydrazine redu according to the method of Mullin and Riley (1955). The r produced was reacted with alpha napthylamine, and the co

E I. Dates of Cruises Made to the New England Coastal Waters

Vessel and Cruise No.	*Date*
Atlantis, 227	10–15 September 1956
Crawford, 8	28 November–3 December 1956
Bear, 159	13–17 February 1957
Bear, 162	21–25 March 1957
Bear, 165	29 April–3 May 1957
Crawford, 13	10–20 July 1957
Bear, 174	16–20 September 1957
Bear, 179	18–23 November 1957
Bear, 181	21–27 January 1958
Bear, 183	6–10 March 1958
Bear, 185	12–16 May 1958
Crawford, 19	7–19 July 1958
Bear, 195	5–8 September 1958

E II. Reproducibility of the Determination of Nitrate-Nitrogen on Standardization Data. Analyses were made in a Beckman DU Spectrophotometer at a Wavelength of 524 mμ

centration Range g-at/l)	*Cell Length (cm)*	*No. of Standards*	*Calibration Factor*	*Standard Deviation (units)*	*($^0/_0$)*
0– 3.75	10	25	5.85	.75	12.9
.0–50	1	67	53.2	7.38	13.9

on was then determined in a Beckman DU Spectrophotometer g a wavelength of 520 mμ. The result will be referred to in this r as nitrate-nitrogen, but both nitrate and nitrite-nitrogen are ded in the analysis. The concentration of nitrite-nitrogen, h has also been determined for these samples, is generally less 10 $^0/_0$ of the nitrate plus nitrite-nitrogen.

e reproducibility of the method has been evaluated by comng standard solutions at various concentrations. Standards prepared by adding known amounts of nitrate to nitrate-free water and, after correcting for reagent blank and for the quantity trate-nitrogen in the sea water used, the factor relating optical ity of the photometer with concentration was calculated for sample. For low concentrations (< 4 μg-at/l) a 10 cm cell has used; the ratio of concentration to optical density is $5.85 \pm .75$, variability of about 13 $^0/_0$ (see Table II). For samples containing

more nitrogen than this, a one centimeter cell was used; an ave
factor of 53.2± 7.38 was found for these concentrations, indica
a variability of about 14 $^0/_0$.

Total nitrogen is the sum of the concentrations of nitrate
nitrite-nitrogen, ammonia nitrogen and amine-amide nitro
Ammonia nitrogen has been determined by the method of R
(1953). Amine-amide nitrogen has been determined by mi
Kjeldahl digestion according to Pregl (1946) followed by distilla
of the ammonia according to Riley (1953).

THE ANNUAL CYCLE IN SURFACE WATERS

Variations in the nitrogen and phosphorus concentrations an
the N:P ratio for surface waters in Sections A-G-J (see Fig. 1)
shown in Figs. 2, 3 and 4. Five of the 13 cruises have been sele
as representing adequately the seasonal variations. The den
structure for the same five cruises is presented in Fig. 5 for c
parison. In July and September, when the density stratificatio
greatest, the concentration of both nutrients in the surface la
is small, the lowest values being observed during the Septem
cruises. In waters below 100 m at these times there is consider
parallelism not only between the distribution of the two nutri
but between each of these and the distribution of density. T
for example, there is always present just off the Continental S
at St. E, a high concentration of nutrients in the same area;
shows as an upward bulge in the density contours. In contr
lower values are found at Sts. G and H where comparable den
contours are at greater depths than at St. E.

By November the density stratification has decreased mark
and surface concentrations of nitrogen and phosphorus have
creased. Over the Continental Shelf, the increases in waters of
than 50 m are accompanied by decreases in waters below 5
indicating that much of the observed change may be due to mi
of the water column rather than to regeneration of nutrients *in*
Beyond the edge of the Continental Shelf, however, the nitr
and phosphorus content has increased below 100 m of depth, i
cating that mixing here has extended to greater depths.

In January, waters over the Shelf are vertically homogeneou
density, and the nutrient concentrations, though much less t
those found in the deeper offshore waters, have reached maxi

for the year. By May, stratification in the water column has
ntensified, both by freshening of the inshore water (at St. A)
y warming of the surface layers. The surface nitrate values
time are almost all less than 1 μg-at/l and the surface phos-
concentrations less than 0.5 μg-at/l—conditions which rep-
closely the concentrations observed in July and September.
ratio of N:P (in atoms) in the surface waters, shown in Fig. 4,
sistently below 5 in July, September and November, with
um values of zero in some of the September observations
ng complete exhaustion of the nitrate. By January the ratio
centration has increased to values generally above 5 in sur-
aters over the Continental Shelf and commonly above 10 at
fshore stations. By May, when the growth of plants has again
ed the supply of nutrients, the ratio of concentration in sur-
waters is again less than 5.

fact that the growth of plants in surface waters over the
reduces the N:P ratio implies that plants are assimilating
elements in a higher ratio than the ratio of concentration
is presented to them. In regard to the constancy of the ratio
ange, Redfield (1934) commented that "it appears to mean
the relative quantities of nitrate and phosphate occurring in
ceans of the world are just those that are required for the
osition of the animals and plants which live in the sea". In
ase of the coastal waters of New England, these elements are
nted to the population in quite a different ratio from the
al 15:1 ratio. It is pertinent to inquire, therefore, whether
coastal populations have become adapted to these low ratios
utilize these elements in a ratio comparable to the ratio of
ntration in the water.

evaluation of the ratio by which biological populations modify
concentrations of phosphorus and nitrogen can be obtained
our data. This is done by plotting one against the other so
the slope of the line joining the high and low concentrations
sents the ratio of *change* rather than that of concentration
has been discussed so far. This has been done for all of the
water samples obtained on the 13 cruises at stations of inter-
ate depth over the Continental Shelf (B, C and D). The results
hown in Fig. 6. The slope of the envelope which encloses the
rity of the points corresponds to the *normal* ratio of *change*
atoms of nitrogen to one of phosphorus. The shaded area

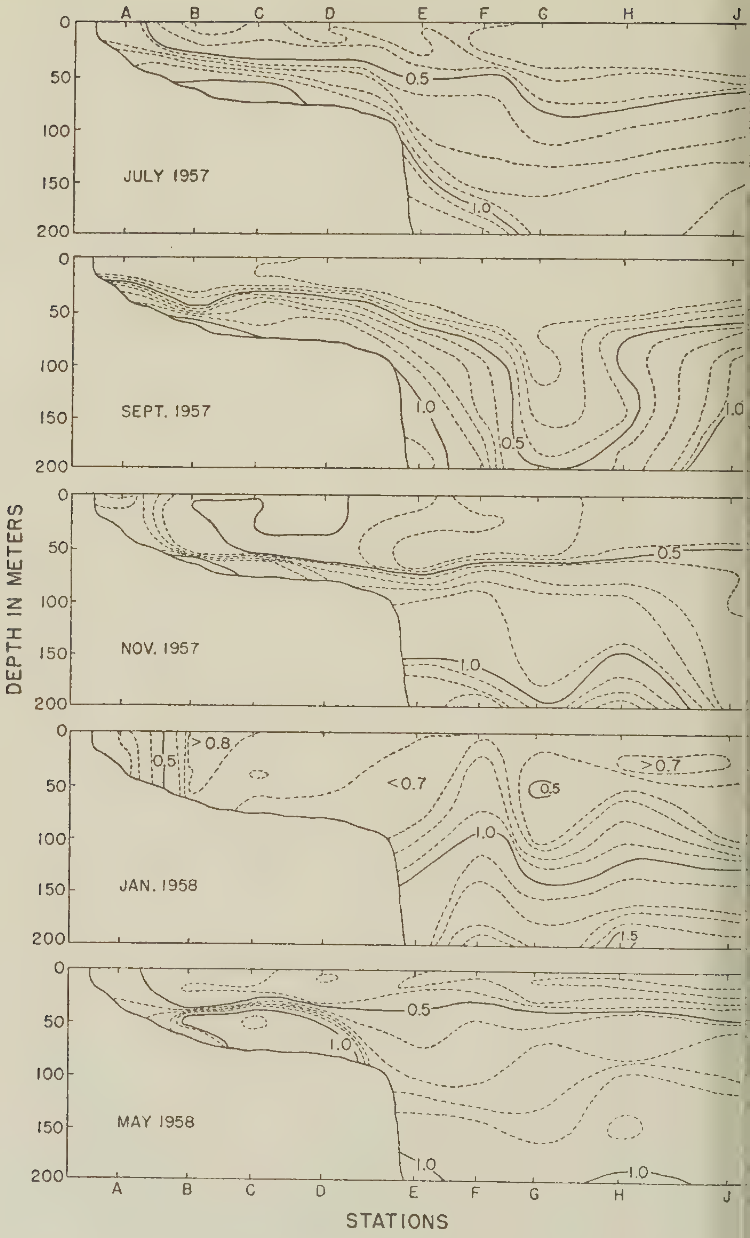


Figure 2. Distribution of inorganic phosphorus (Vertical exaggeration 400:1)

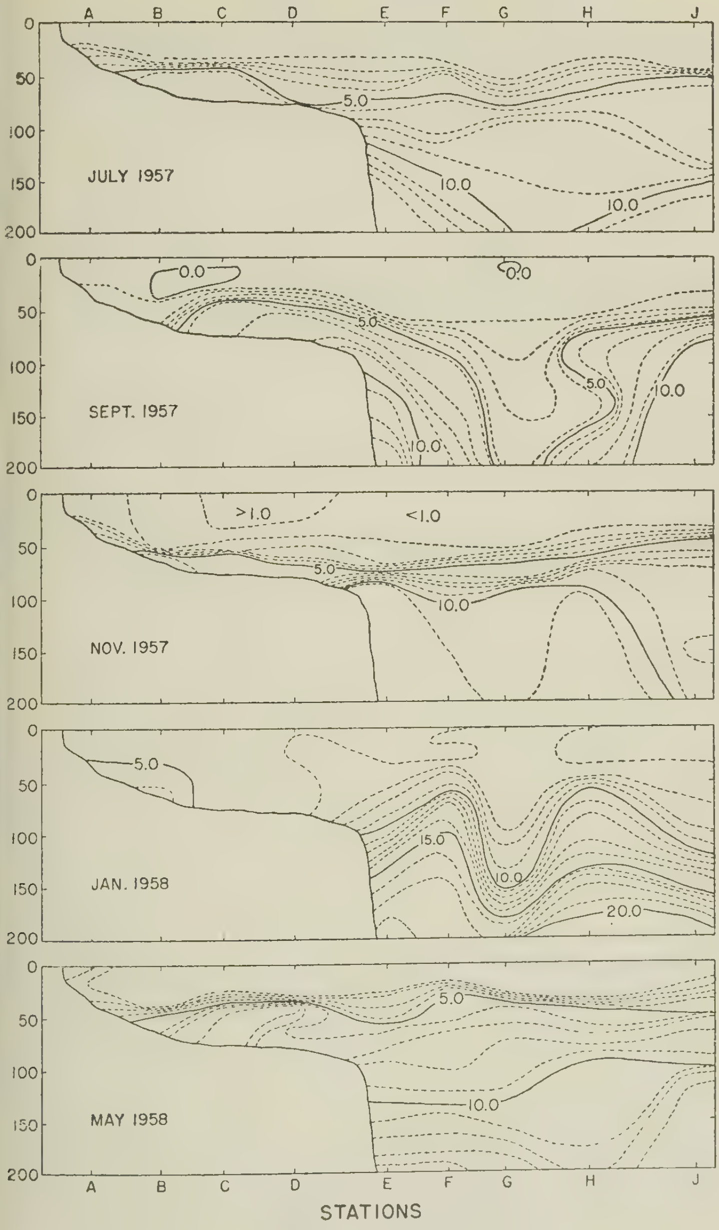


Figure 3. Distribution of nitrate-nitrogen.

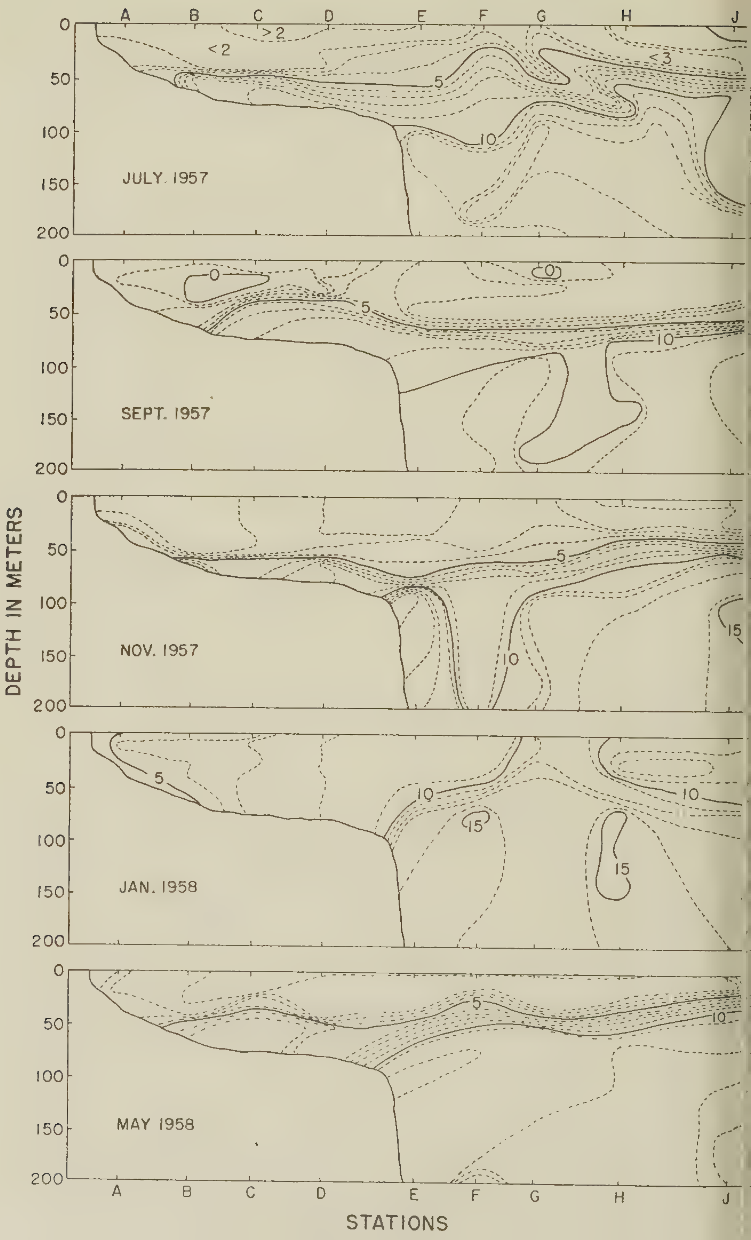


Figure 4. Distribution of N:P ratios.

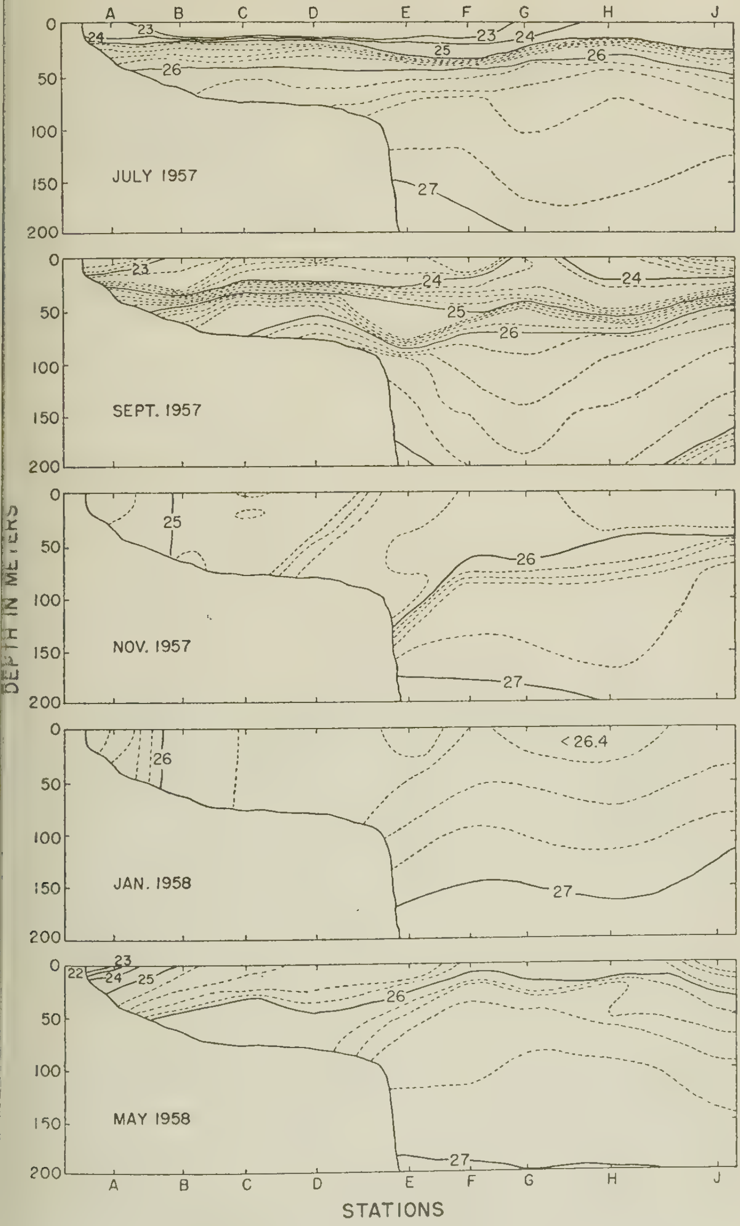


Figure 5. Distribution of density (σ_t).

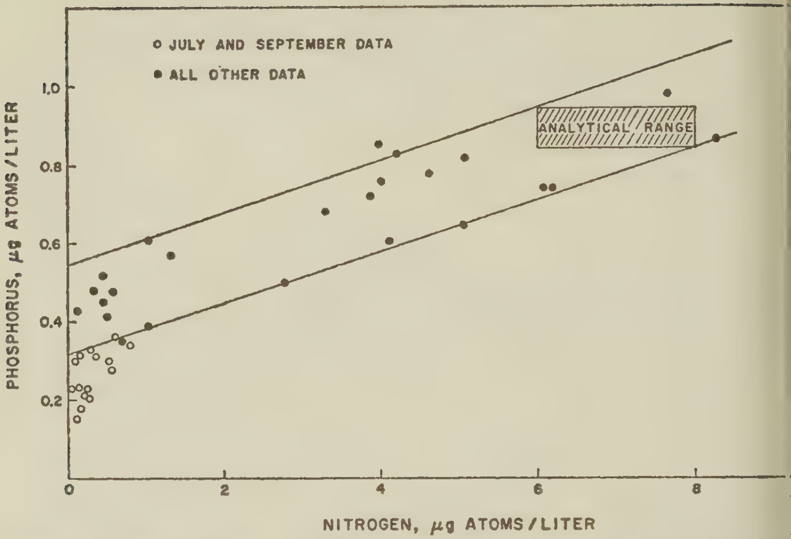
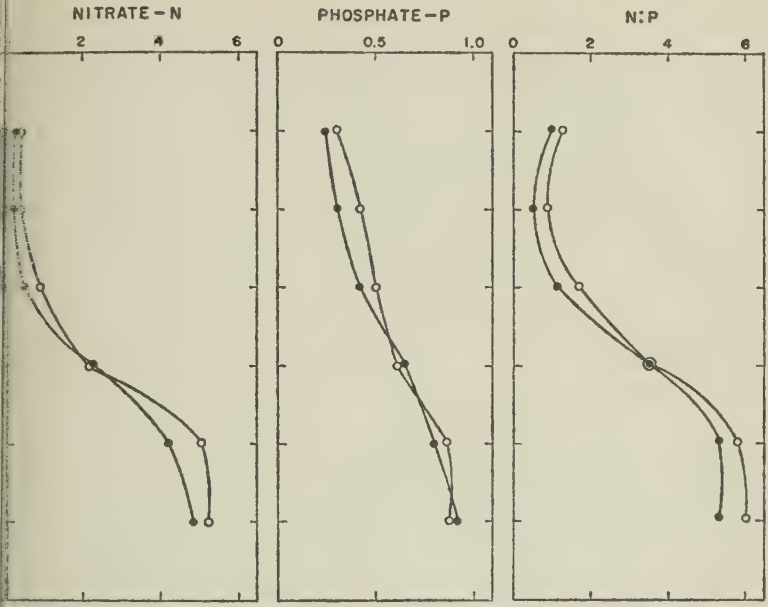


Figure 6. Ratio of change, $\Delta N{:}\Delta P$, for the 10 m samples at Sts. B, C, D. The sl
the envelope corresponds to $\Delta N{:}\Delta P = 15{:}1$.

labeled *analytical range* corresponds to a variation of ±0.05 μg-a
and ±1.0 μg-at N/l. All of the observations made in July and
tember (open circles) suggest a lower ratio of *change* during t
months, when concentrations, especially of nitrate, are extre
low. Throughout most of the year, therefore, the biological p
lations in this part of the ocean, where they are exposed t
abnormally low N:P ratio, are assimilating (and regenerating) n
gen and phosphorus in the *normal* ratio of 15:1. In the period
to September, however, when nitrogen concentrations are less
1 μg-at/l, the populations are able to assimilate relatively
nitrogen while still reducing the phosphorus concentration.
may imply accomodation to the abnormal ratios at these low
centrations.

The intercept of the envelope noted above corresponds to ex
phosphorus concentrations lying between 0.32 and 0.55 μg-at/l
course this excess is reflected in the low N:P ratios of concentra
becoming increasingly important as their concentrations are
minished.

It should be pointed out that neither vertical nor horizontal
ing processes in this area can account for a ratio of change of



re 7. Average vertical distribution of nitrogen, phosphorus and the N:P ratio at
s of intermediate depth (B, C, D); open circles, September; solid circles, July.

hese two elements. However, it was suggested by Mr. John
e that mixing must supply, in large part, the phosphorus and
gen required by the populations while the concentrations in
ce waters are low. The ratio in which these two elements would
pplied by mixing is considerably higher than the ratio of their
entrations in the surface waters. The vertical distributions of
gen, phosphorus, and of the N:P ratio at Sts. B, C, and D are

E III. Gradients of Nitrogen and Phosphorus in July and September at Sts. B, C, and D. Mean Concentration in μg-at/l.

	Nitrate-N			*Phosphorus*			
	Surface	*Deep*	*Difference*	*Surface*	*Deep*	*Difference*	*$\Delta N:\Delta P$*
nber 1956	.23	3.78	3.55	.35	.93	.58	6.1
1957	.63	6.07	5.44	.35	.86	.51	10.7
nber 1957	.13	5.56	5.43	.21	.86	.65	8.4
1958	.46	4.11	3.65	.44	.91	.47	7.8
nber 1958	.48	3.96	3.48	.40	.74	.34	10.2

shown in Fig. 7. The data have been averaged at each depth three September cruises and for two July cruises.

Vertical mixing will bring these elements to the surface wa at rates proportional to the gradient of concentrations. For cruise this gradient has been evaluated by comparing average the 10, 20 and 30 m observations with those taken at 50 and 6 The results given in Table III. The differences listed are gradients over a depth of 20 m, and the ratio at which nitr and phosphorus will be delivered to the surface waters by mi is given by the ratio of these gradients. They range from 6.1 to all much higher than the ratio of concentration in the surface wa Thus, while populations in the surface waters are living in a med with an abnormally low N:P ratio, the conditions are not as normal as would be suggested by the observed ratio of concen tions. The fact that mixing, at these times, does not increase ratio of concentration in the surface waters suggests that the p lations assimilate these elements as rapidly as they become avail

Another source of supply of nitrogen and phosphorus is the composition of organic materials *in situ*. In Table IV the rati

TABLE IV. Average Inorganic and Total N:P Ratios (by Atoms) for Water Samples at Stations of Intermediate Depths on the Contin Shelf

Cruise Date	*Inorganic*	*Total*
September 1956	1.21	16.3
November-December 1956	4.55	25.9
February 1957	5.78	15.9
July 1957	2.41	30.2
September 1957	1.55	23.1
November 1957	1.81	21.0
January 1958	7.08	14.9

total nitrogen to total phosphorus is compared with the inorg ratio observed in the 10 m samples for stations of intermed depth on various cruises. Some of the cruises have been om because ammonia and amine-amide nitrogen, necessary to d the total, were not determined. The ratio of concentration of N:total P is considerably higher than the ratio of the inorg concentrations. Decomposition of the organically combined n gen and phosphorus would thus supply the populations with s of these elements. Presumably all of the organic phosphorus pounds are ultimately decomposed, since the concentration of nic phosphorus is negligible in deep waters (Ketchum, *et al.*,). The deep waters, however, contain considerable amounts of ned nitrogen, as indicated by Krogh (1934) and by von Brand Rakestraw (1941), and storage in the laboratory does not apably decrease the concentration. This suggests that some of rganic nitrogen in sea water is not readily decomposed, but not known how much of the organic nitrogen is available for bolism of the populations.

VARIATIONS IN DEEP WATER

Sts. G, H and J (Fig. 1), samples were taken to depths of m. In deep waters, of course, photosynthesis is not possible use of the lack of light. However, decomposition of organic rial sinking from surface layers at these stations might be cted to give seasonal changes in the concentrations of nitrogen phosphorus.

order to permit comparison of the results, concentrations of gen and phosphorus at depths greater than 100 m have been ted against density (σ_t). This was done for the cruises which made between February 1957 and May 1958 inclusive, with exception[2]. Thus results from three stations were available, and each cruise an average curve relating nitrogen and phosphorus ensity was constructed. These average curves were then traced single graph, and the envelope in Fig. 8 describes the range of entrations observed at various times of year.

hroughout most of the water column the range of variation in nitrogen and phosphorus concentrations is no more than would xpected from analytical variation. The values of the maximum entration for each cruise are presented in Table V. The average

Results of Bear cruise 165 made in April and May 1957 are not included in reatment. In the nitrate analysis, calibration of the one centimeter cell gave alously low color development, and results calculated with the factor from alibration are all considerably lower than any for the other cruises. We believe for some reason, reduction by the hydrazine in the high concentrations was plete for this set; however, the calibration and the concentrations for the dilute samples measured in the 10 cm cells were apparently satisfactory and been used in the previous section.

concentration of nitrate-nitrogen at the maximum was 20.7 μg-a
with a standard deviation of ±1.97. This corresponds to a variati
of approximately 10 $^0/_0$, which would be expected for this analy
The average phosphorus concentration was 1.65 μg-at/l, witl
standard deviation of 0.11, or about 7 $^0/_0$. This variation is also
be expected from analytical errors.

The N:P ratios vary from 11.2 to 14.6 at the maximum conc
tration of these elements, with a mean value of 12.5. Even for
deep waters immediately off the Continental Shelf in this regi
therefore, there is an excess of phosphorus over nitrogen, produc
a low N:P ratio.

For all depths at the deep stations, the concentration of phospho
has been plotted as a function of the concentration of nitrogen.
of the results for each cruise can be enclosed in an envelope wit

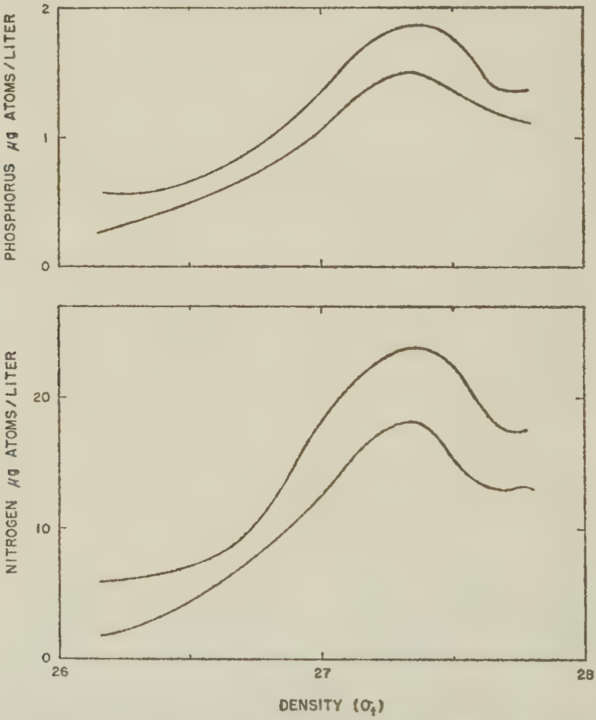


Figure 8. The relationship between phosphorus and nitrogen and the density of
water at depths greater than 100 m. The envelope describes the maximum range of
centrations observed at various times of year.

LE V. Maximum Concentrations of Inorganic Phosphorus and Nitrate-Nitrogen in μg-at/l at Sts. G, H and J

Date	*Phosphorus*	*Nitrogen*	*N:P (atoms)*
February 1957	1.86	20.8	11.2
March 1957	1.72	19.8	11.5
July 1957	1.63	20.0	12.3
September 1957	1.64	18.2	11.1
November 1957	1.52	18.8	12.4
January 1958	1.54	22.5	14.6
March 1958	1.67	24.2	14.5
May 1958	1.62	21.4	13.2
Mean	1.65	20.7	12.5
Standard deviation	0.11	1.97	—

of 15 atoms of nitrogen to 1 of phosphorus, provided it is as- ed that the waters contain excess phosphorus, *i. e.*, the median of the envelope intercepts the ordinate at a phosphorus concen- on greater than zero. However, the width of the envelope ex- s the standard deviation of the method of analysis. The excess phorus determined by extrapolation and the ranges of variation presented in Table VI. The mean value for excess phosphorus he deep stations is 0.22 μg-at/l, somewhat less than that found

LE VI. Relationship between Nitrogen and Phosphorus in μg-at/l at G, H, J. The Excess Phosphorus is the Intercept of the Median Line Envelope Enclosing all Points, having a Slope of $\Delta N:\Delta P = 15:1$. Range is the Distance from the Median Line to the Boundaries of the Envelope

Cruise	*Exess P*	*Envelope Range*	
		P	*N*
September 1956	0.31	±0.30	±4.5
November 1956	0	±0.25	±3.8
February 1957	0.25	±0.25	±3.8
March 1957	0.25	±0.25	±3.8
July 1957	0.35	±0.35	±5.25
September 1957	0.25	±0.25	±3.8
November 1957	0.25	±0.25	±3.8
January 1958	0.13	±0.22	±3.3
March 1958	0.22	±0.28	±4.2
May 1958	0.26	±0.25	±3.8

for the shallow inshore waters, which ranged from 0.32 to 0.5 Variations in the data, as defined by the distance between t envelope and median line, are generally two or three times t standard analytical deviation, even at the highest concentrations o served (*c. f.* Table V). This excess variation, suggesting inhomogenei in the water masses, is as yet unexplained. These differences a apparently not accompanied by related variations in either tempe ature or salinity of the water, which would have been apparent the plots as a function of density (Fig. 8). They thus demonstra an inhomogeneity which would have escaped detection by the usu oceanographic techniques.

DISCUSSION

In his original paper on the proportions of organic derivatives sea water, Redfield (1934) speculated that biological processes mig determine these proportions. He has recently (1958) presented discussion of the ways in which this could be accomplished. It also possible, of course, that the sea, when it originated in eo past, had concentrations of the essential nutrients in the sa proportions as the sea today. The fact that marine organisms, a indeed all living matter, contain in their protoplasm nitrogen a phosphorus in approximately the same ratio as they are found the deep sea would then be attributed to the adaptive ability the biological system. Ketchum (1939) showed that, for a giv concentration of phosphate, the marine diatom *Nitzschia closteri* (*Phaeodactylum tricornutum*) absorbs constant proportions of pho phorus and nitrogen from the water, regardless of the ratio of th concentration. As the concentration of phosphorus in the mediu was increased, the ratio of assimilation (($\Delta N:\Delta P$) decreased. variation was apparent with nitrogen concentrations at consta phosphorus except when the nitrogen content was less than 1 μg-at which produced low values for the ratio of assimilation. Ketchu (1939a) showed that, when either nitrogen or phosphorus was e hausted from the water, the plants continued to grow and divi but developed a deficiency in the internal concentration of the e hausted element. The maximum nitrogen deficiency in *Chlore pyrenoidosa* produced an internal N:P ratio of 2.35 (by atoms) a the maximum phosphorus deficiency produced a ratio of 31.2.

Our observations on surface coastal waters confirm these co

ns. In spite of the anomalously low N:P ratio, plants apparently
ilate these nutrients in the *normal* ratio of 15:1 until ex-
ly low concentrations are reached. At such times the cells can
ently assimilate relatively little nitrogen while still depleting
osphorus which is present in excess. It would clearly be de-
to have analyses of photyplankton collected in September,
the low ratio of assimilation is inferred to have taken place
period of about three months. Harris and Riley (1956) did
such analyses of phytoplankton growing in Long Island Sound,
the ratio of concentrations is comparable to that found in
astal waters. Their average value for the N:P ratio in phyto-
on was 16.7:1, suggesting that the plants generally main-
a high ratio of composition in spite of the low ratio of con-
tion in the waters in which they had grown. However, their
value, 13.1:1 by atoms, was obtained in August, approx-
ly four months after the nearly complete removal of nitrogen
the water, as shown by Riley and Conover (1956).

nearly complete assimilation of nitrate-nitrogen from the
e waters suggests that it may be an important nutrient lim-
n to the growth of phytoplankton. Phosphorus is always pres-
some excess in these waters, hence it may not be limiting,
ugh its concentration does fall below the value of 0.55 μg-at/l,
ently quoted as limiting the rate of phytoplankton growth
hum, 1939). The nutrient concentrations in surface waters did
ange appreciably from July to September. Ryther and Yentsch
) have shown, however, that phytoplankton production con-
during this period, but at a low rate. This production must
pported by nutrients supplied through turbulent mixing or
generation *in situ*. Both of these processes require more
us evaluation.

r observations emphasize the dangers inherent in an inter-
tion of the nutritional status of plankton populations from
vations of only one nutrient element. It is probable that a
complete understanding of phytoplankton periodicity will
e observations not only of nitrogen and phosphorus but of
nutrients as well.

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RADIUM CONTENT OF CARBONATE SHELLS[1]

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ABSTRACT

Radium determinations have been made for shells from Swedish waters Mediterranean Sea and the Pacific Ocean. Their Ra/Ca ratio has been estim and compared to the Ra/Ca ratio in sea water. It was found that, in general Ra/Ca ratio is proportional to the Sr/Ca ratio found by Thompson and Cho

Removal of radium from surface waters changes the radium content of the w It is estimated that the rate of this precipitation is of the same order of magn as the rate of decay of radium in the water. Since radium is also taken up by pl plankton, it is concluded that the apparent half-life of radium in surface w is only one-third of the natural decay constant.

INTRODUCTION

Approximately 50 years ago, Joly (1908) found high radium va in red clay samples taken on the Challenger Expedition; sequently Joly's measurements were confirmed by both Petter (1930) and Piggott (1933), and later Pettersson (1937) explai these high values. With continued study of the distributior natural radioactive elements in marine environments, Petter and Rona (Føyn, *et al.*, 1939) published radium determinations f 23 water samples, and more recently Pettersson (1955) and K (1953, 1955) have contributed further data on radium in sea w and in sediments. Koczy (1954, 1956) has surveyed the com problem of distribution in the ocean of elements in the uran and radium series; and Koczy, *et al.* (1957), who have estim the amount of ionium precipitated in sea water, have shown the radium in sea water is derived mainly from radium produ

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[1] Contribution No. 255 from the Marine Laboratory, University of Miami, Gables, Florida.

ottom sediments, thus confirming the ionium precipitation
thesis of Pettersson.

order to use the vertical distribution of radium to trace the
nge of deep water with surface water and to use its horizontal
ution to deduce the kinematics of water masses, the processes
ning the concentration of radium in the surface layer must be
stood. The most important factor in the removal of radium
upper layers is the activity of organisms. If an organism pre-
ted radium and calcium from surface layers in the same ratio
t found in the water, then the amount of radium precipitated
be estimated from the amount of calcium carbonate precipi-
The calcium carbonate precipitated as a result of biological
ty might then be estimated from the sedimentation rate of
gerina ooze, which might be assumed to be not less than
n^2/year. However, this estimate is too conservative, and it is
reasonable to assume that 25 g CaCO$_3$/m^2/year are precipitated
a layer 500 m thick. This is equivalent to precipitation of
g CaCO$_3$/m^3/year, or 0.005 $^0/_0$ of the total calcium in sea water
t 400 g/m^3). If radium is proportionately incorporated into
s, 3.5×10^{-15} g Ra/m^3/year (assuming Pettersson's value of
)$^{-14}$ g Ra/L), or 1.75×10^{-12} g Ra/m^2/year, should be precipi-
in the upper 500 m. This quantity is about 0.05 $^0/_0$ of the
nt of radium in a 50 m column of water one meter square;
dium precipitation is concentrated in the upper 50 m, where
of the biological activity is also concentrated, the amount
d be equal to that which disappears by natural decay. It might
ssumed also that part of the radium is incorporated into silica
s.

ree problems, therefore, need to be considered: (1) quantitative
ates of carbonate precipitation in sea water; (2) determination
e Ra/Ca ratio in calcareous organisms and skeletons; and
ncorporation of radium into carbonate-poor organisms and
tons.

is paper, dealing primarily with Ra/Ca ratios in calcareous
nisms, presents only part of a study of the concentration, up-
, and leaching of radium in carbonate shells; some of the shells
yzed were collected during the Swedish ALBATROSS Expedition
7–1948) while others were obtained in Sweden. The parts of
study that will be published elsewhere will treat (1) the radium
ent of shells of lobsters and mollusks grown in an aquarium

with artificially increased radium content, and (2) the radium
tent of postglacial shells 5,000–10,000 years old. E. Tomic
F. Hecht determined the uranium in some of the samples, for w
the authors wish to express their sincere gratitude.

METHODS AND RESULTS

Radium. These determinations were made according to the p
ciples given by Kropf (1939) and described by Kröll (1955).
samples were dissolved in 50 to 100 ml hydrochloric acid to w
10 to 50 ml n-butyl alcohol (p.a.) had been added to eliminate fo
ing. After the evolution of gas ceased, the solution was evapora
to dryness. The salts were allowed to cool, after which concentra
hydrochloric acid and 10 to 30 ml of 70 % perchloric acid
added; then the solution was again evaporated to dryness. The
maining salt was fumed with a mixture of chloric and perchl
acids until it was completely white or slightly yellow (iron). Fina
the salt was dissolved in dilute hydrochloric acid and filtered.
solution was put into a specially designed bottle suitable for
final transfer of the accumulated emanation into the ion cham
Fresh plankton was fused in a mixture of K_2CO_3 and Na_2CO_3
nickel crucibles, so as to convert the silica into soluble form.
main part of the organic matter was removed before the fusi
were carried out.

The ionization current caused by the decay of radium emana
was measured with a Wulf Electrometer, and the natural backgro
was balanced by a second ionization chamber with a reversed cha
Nitrogen, at least three weeks old, was used as a neutral filling
Before the mixture of radioactive material and nitrogen was
into the chamber, it was dried with magnesium perchlorate.
sensitivity of the electrometer, 3.02×10^{-13} g Ra/degree, was
trolled by radium standards. The amount of sample used
determined by the expected radium content. The error of estima
increased rapidly below a total radium content of 10^{-12} g. S
samples, less than 30 g of postglacial shells and a few grams of
others, were used in order to be able to process them quickly.
the present samples, the accuracy of measurements, discussed
Koczy (1949), is estimated to be better than 20 % and is, on
average, ± 10 %.

BLE I. RADIUM, CALCIUM, AND URANIUM CONTENT OF RECENT SHELLS

	Locality	*Date of Sampling*	*Weight* (*g*)	*Ra* (*10*$^{-13}$*g*/*g*)	*Ca* (*g*/*g*)	*U* (*μg*/*g*)	*Ra*/*Ca* (*10*$^{-13}$)
USCA							
ASTEROPODA							
PROSOBRANCHIATA							
um undatum	Lysekil	Sep 1956	9.206	0.52	0.383	—	1.36
ea tigris	No data	—	21.534	1.19	0.392	—	3.03
ea speciosus	No data	—	20.851	0.45	0.389	—	1.15
a littorea	Hovås	Jul 1956	23.467	0.19	0.373	—	0.51
brandaris	Monaco	May 1956	20.334	0.19	0.379	—	0.502
reticulata	Hovås	Jul 1956	16.798	0.25	0.385	—	0.649
carolea	Monaco	May 1956	20.199	0.15	0.379	—	0.395
us speciosus	No data		22.360	0.80	0.390	—	2.05
cetosus	No data		21.284	1.06	0.378	—	2.80
LAMELLIBRANCHIATA							
um edule	Hovås	Jul 1956	20.430	0.66	0.390	—	1.69
um echinatum	Lysekil	Sep 1956	7.800	0.96	0.378	—	2.54
na islandica	Bornö	—	24.831	0.45	0.383	—	1.17
us edulis	Hovås	Jul 1956	21.301	0.71	0.389	—	1.83
us edulis	S. Själh	Sep 1956	13.027	1.17	0.374	1.32	3.13
us edulis	S. Själh	Sep 1956	15.891	1.36	0.380	1.70	3.58
us edulis	Skår	Sep 1956	15.107	0.32	0.380	0.52	0.842
us edulis	W. Bornö	Sep 1956	13.658	0.69	0.383	0.97	1.78
us edulis	ö.l.Bornö	Sep 1956	20.821	0.32	0.376	2.13	0.852
us edulis	ö.l.Bornö	Sep 1956	31.277	0.41	0.364	—	1.113
us edulis	ö.l.Bornö	Sep 1956	18.126	0.41	0.378	—	1.00
us edulis	Saltällefj.	Sep 1956	22.123	0.39	0.378	0.82	1.03
us gallaprovin- lis	Monaco	May 1956	21.134	0.29	0.377	—	0.769
*edulis**	No data	—	26.338	0.14	0.391	1.27	0.359
*edulis**	No data	—	60.167	0.20	0.390	1.27	0.513
va artica	Hovås	Jul 1956	20.490	1.27	0.388	—	3.27
ovata	Lysekil	Sep 1956	10.351	1.11	0.381	—	2.91
CEPHALOPODA							
officinalis		Sep 1939	20.766	0.43	0.356	—	1.21
TACEA							
ENTOMOSTRACA							
CIRRIPEDIA							
us sp.	Oskär	No data	21.283	1.92	0.374	—	5.14

ame sample.

TABLE I (continued).

	Locality	*Date of Sampling*	*Weight (g)*	*Ra (10^{-13}g/g)*	*Ca (g/g)*	*U (µg/g)*
Class Malacostraca						
Order Decapoda						
29. *Cancer pagurus*	No data	Nov 1956	17.896	0.55	0.276	—
30. *Carcinus maenas*	Lysekil	Jun 1940	21.883	0.97	0.274	—
31. *Nephrops norvegicus*	Lysekil	Jun 1940	5.269	1.42	0.175	—
32. Fresh Plankton†	No data	Mar 1939	18.470	2.75	0.00454	—

† 34.22 $^0/_0$ organic matter; 65.57 $^0/_0$ SiO_2 a.o.; 0.21 $^0/_0$ $CaCO_3$.

Calcium. After all measurements of radium were completed, samples were brought to equal volumes by adding distilled w to facilitate sampling for determination of calcium by precipita and determination as calcium oxalate. The method of Tread (1951) was used with slight modifications. Results of the anal are given in Table I.

The values given in Tables I and II are the means of two de minations and have a maximum error of $\pm 0.3\ ^0/_0$.

TABLE II. Comparison of the Ca and Ra/Ca Values with the Ca and S Values

Group	*According to Koczy and Titze* Ca (g/g)	*According to Koczy and Titze* Ra/Ca (× 10^{-13})	*According to Thompson and Chow (* Ca (g/g)	*According to Thompson and Chow (* Sr/Ca (× 10^{-3})
1. Ostreidae	0.390	0.435	0.362	1.22
2. Littorinidae	0.373	0.510	0.381	1.53
3. Muricidae	0.379	0.502	0.382	1.62
4. Nassariidae	0.385	0.649	0.364	1.89
5. Pleurophoridae	0.383	1.17	0.392	1.57
6. Dibranchiata	0.356	1.21	0.358	3.74
7. Mytilidae	0.378	1.60	0.383	1.56
8. Veneridae	0.381	2.91	0.383	1.86
9. Saxicavidae	0.388	3.27	0.380	2.42
10. Eucarida	0.242	4.55	0.248	6.16
11. Thoracica	0.374	5.14	0.336	4.44

DISCUSSION

Ratio of Radium to Calcium in Shells. According to Føyn, (1939), the average content of radium in the North Sea and e Skagerrak is 0.7×10^{-13} g Ra/l. Surface waters of the ocean in about 0.5×10^{-13} g Ra/l. The calcium content of sea water g Ca/l. Therefore the ratio of radium to calcium in sea water out 1.33×10^{-13} and may be as high as 2.5×10^{-13}. The Ra/Ca obtained from shells are about the same, varying between d 5.0×10^{-13} (Table I). It might be concluded, therefore, that radium nor calcium is taken up by organisms in preference other; however, systematic differences were found among ent orders and families of organisms. The smallest Ra/Ca ratio nd in the oyster (*Ostrea edulis*), the highest in crustaceans.

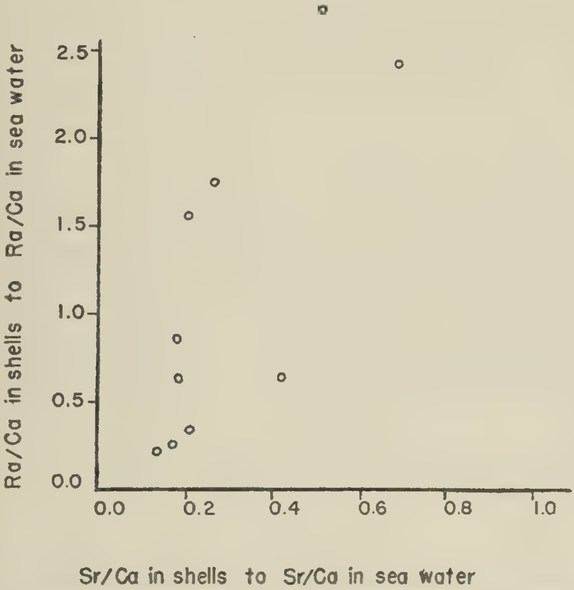
e variation of the Ra/Ca ratio with locality was investigated e blue mussel (*Mytilus edulis*, samples 14--21). Two specimens in the Skagerrak and others taken in the interior of Gullmars- at varying distances from the mouth showed that both the m and the calcium contents decreased with a decrease in ity. The variation in salinity of the surface water in Gullmars- is between the limits of 36 and 15 $^0/_{00}$; *i. e.*, the lowest salinity out half of the maximum. Two samples of river water gave an ge radium content of $0.65 \pm 0.5 \times 10^{-14}$ g Ra/l (0.0 and $1.3 \pm$ 10^{-14} g Ra/l) and a calcium content of the order of 30 mg/l. the river water should show about the same Ra/Ca ratio as water. Consequently, mixing of salt water and river water in l ratio should not alter the Ra/Ca ratio from that of sea water than a few percent. The decrease in the Ra/Ca ratio of shells ne third must then result from some mechanism other than ability of the ions. It is clear that, within this locality, the m content of shells is constant within the limits of the error eterminations, as is demonstrated by samples 18, 19, and 20. ree samples from the Mediterranean (samples 5, 7, and 22) very low radium contents. *Mytilus gallaprovinciallis* (22) has smallest radium content of all the mytilids analyzed. This is ably a consequence of the lower radium content in the surface r of the Mediterranean Sea (0.6×10^{-13} g Ra/l compared with 10^{-13} g Ra/l in the Skaggerrak; Pettersson, 1955), but the a ratio may also be influenced by the growth rate of organisms. esh plankton from the North Sea, included because of its high

Ra/Ca ratio in spite of its low calcium content, had the hig
radium content of all samples: 2.75×10^{-13} g Ra/g. Plankton org
isms apparently play an important role in the removal of radi
from ocean water, and the high rates of production and high stand
crops of plankton in temperate waters may influence the remo
of radium from surface layers.

Comparison of Ra/Ca and Sr/Ca Ratios in Carbonate Shells. Si
radium has chemical properties similar to strontium, differing mai
in its ionic radius, it might be assumed that radium would be ta
up preferentially by organisms which take up strontium prefer
tially. Thompson and Chow (1955), who determined the stronti
content of many shells, found a rather high variation in the Sr
ratio. In Table II, results of the present investigation, grouped
families or orders, are compared with Thompson and Chow's
sults. Mean values, where available, or single values arranged
cording to increasing radium content, are shown.

Generally, families of organisms having high Ra/Ca ratios
have high Sr/Ca ratios. These are the Saxicavidae (*Mollusca, Lam*
branchiata), Thoracica (Crustacea, Cirripedia), and Eucarida (C
tacea, Decapoda). Only the Dibranchiata (Mollusca, Cephalopo
have high strontium and low radium contents. One may define
enrichment factor for strontium as the Sr/Ca ratio in shells to
Sr/Ca ratio in sea water and the corresponding enrichment fa
for radium as the ratio of Ra/Ca in shells to the Ra/Ca ratio in
water. Fig. 1 shows a positive correlation between these two fact
Eucarida and Thoracica have Sr/Ca ratios of about 60 $^0/_0$ of t
in sea water, while the other groups listed in Table II have a c
siderably smaller ratio, about 20 $^0/_0$ of that in sea water. Oys
had not only the lowest Ra/Ca ratios but the lowest Sr/Ca ra
as well. As shown in Table II, the Ra/Ca ratio, varying betw
20 and 250 $^0/_0$ of that of sea water, is more widely spread than
Sr/Ca ratio. This larger variation in the Ra/Ca ratio may be due
large variations in the radium content of sea water, for, althou
a radium content of 0.75×10^{-13} g/l has been assumed for th
calculations, ALBATROSS samples taken in the open ocean gave s
face values of radium varying from 0.3 to 0.9×10^{-13} g/l. Now,
strontium content of sea water is apparently as constant as
calcium content. Hence, the larger variability in radium cont
could cause a spread of the Ra/Ca ratio, masking groupings in

a ratio. The variations of radium in surface waters depend
nly on the quantity and rate of supply of deep water but on
eochemical history of the particular water mass.
e fact that the radium factors are higher than the strontium
rs is surprising, since radium, having a larger ionic radius,



1. The relationship between the ratios of Ra/Ca and Sr/Ca in shells and those of
ter.

ld be more difficult to incorporate in shells. But the incorpor-
n of radium may be governed by mechanisms other than sub-
tion into the crystal lattices and by its extremely low concen-
on in sea water. This would make comparison of the two en-
nent factors on the basis of mixed crystals irrelevant.

SUMMARY

adium determinations for a number of shells show that this
ent is extracted from sea water to about the same extent as is
um. In general, the Ra/Ca ratio of shells is proportional to the
a ratio found by Thompson and Chow (1955) and it seems to

be characteristic for each organism and environment. Radium removed from surface layers of the ocean by the activity of ca careous organisms at about the same rate as it decays, provid a total carbonate removal of 25 g/m^2/year is assumed. The remov of radium from sea water by planktonic organisms is difficult estimate. It is almost impossible to determine the total amount organic material which is removed from the surface layer becau it is not known whether radium is accumulated in the skeleton in the organic parts of these organisms. However, if we assume th the average production of plankton is about 40 gC/m^2/year (co responding to approximately 100 g dry weight of organic matte it may be assumed also that about 1 $^0/_0$ of the annual producti of living matter is removed from surface layers. The radium conte of one sample of plankton was found to be 2.75×10^{-13} g Ra/g; t same amount must be removed per square meter per year. This of the same order of magnitude as the removal of radium by ca careous shells, thus reducing the apparent half life of radium in su face water to about $^1/_3$ of the natural decay constant.

Thus the horizontal distribution of radium may give indicatio concerning the movements and mixing of surface water. Althou current speeds may not be obtained in this way, the direction currents may be so estimated.

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CHEMICAL DETERMINATIONS OF NET PLANKTON, WITH SPECIAL REFERENCE TO EQUIVALENT ALBUMIN CONTENT

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Herrn Prof. Dr. Th. Thompson zum 70. Geburtstag gewidmet.

ABSTRACT

Organic substance, total nitrogen and the albumin equivalent were determined by analysis in 23 net plankton samples; ten of these were also analyzed for dry substance following rough microscopic examination. Wide variations were found in all components. The following average values were calculated from the analyses:

Group	$^0/_0$ *DS*	$^0/_0$ *OS on DS*	$^0/_0$ ΣN *on DS*	$^0/_0$ *Alb. Eq. in OS*	$^0/_0$ *Alb. Eq.N in* ΣN
DIATOMS	11.0	53.7	5.6	20.4	58.3
CERATIA	11.6	84.7	5.0	21.8	70.0
COPEPODS	13.6	91.5	9.2	37.3	63.2
MIXED PLANKTON	—	78.2	6.8	24.4	58.2

These analyses agree fairly well with those of other workers, excepting Brandt and Raben's figures for total nitrogen, which are much higher. The albumin equivalent may serve as a good indicator of the active substance in live plankton and of the organic substance as well. The range of variation of the albumin equivalent is narrower (14.4 to 28.5 $^0/_0$ of organic substance) than that of the organic substance in dry substance (36.2 to 95.4 $^0/_0$) in phytoplankton, and is narrower still in mixed plankton (22.7 to 25.9 $^0/_0$ as against 64.3 to 89.8 $^0/_0$). Thus determination of the albumin equivalent (analytically feasible down to 10 μg) may have some advantages in routine analyses at sea for estimating the standing crop of plankton and its mineralization potential.

INTRODUCTION

Since the early chemical analyses of marine plankton by Hensen (1887) and by Brandt and Raben (1922), there have been few additional investigations of this nature. However, some problems of modern plankton research, particularly those of production biology, call for more exact knowledge than is now available; *e. g.*, annual cycles in the chemical composition of the principal plankton groups.

owever, collection of satisfactory planktonic material involves
onsiderable difficulties, especially if analyses of single species or
enera are desired, inasmuch as normal plankton samples almost
lways represent mixtures of widely differing systematic units. On
he other hand, extrapolation of analyses of pure cultures is hardly
easible; even if culture conditions approximate nature very closely,
rofound differences in qualitative and quantitative chemical com-
osition may be expected.

So one would have to await the more or less accidental occurrence
f comparatively pure stocks unless one is studying organisms large
ough to be isolated from a catch. For phytoplankton, excepting
me large Coscinodisci, such isolation under the microscope is
ardly practicable. However, not so for the zooplankton, in which
ase one may readily isolate suitable quantities (*e. g.*, copepods)
or analysis, as was done by Marshall, *et al.* (1933) in their admirable
tudy on the chemical composition of *Calanus finmarchicus*. In
hat work, year-round analyses of females, males and stage V for
at and total nitrogen were performed. Such investigation is needed
or all principal groups of plankton, but for the time being we must
e content with analyses of natural populations of reasonable purity
nd accept their contamination with detritus and bacteria.

The plankton analyses here reported are intended to serve two
urposes: (1) to supplement our knowledge of the composition of
et plankton with analyses of dry substance (DS), organic substance
OS), total nitrogen (ΣN), and protein; (2) to study the ratio of ΣN
o protein in particular, a ratio that is of special interest in research
n biological productivity. In such inquiries it is desirable to deter-
mine either the catabolic output per unit time or its net proceeds,
. *e.*, the stock of planktonic substance formed. This stock might be
pecified either as numbers of systematically defined individuals or
s biotic mass in unit weight of fresh substance. However, the con-
ept of biotic mass fails to take into account the great diversity of
omposition. To be sure, it would be convenient if one could deter-
mine the OS formed, at least for material from the high seas where
he picture would not be falsified by allochthonous OS, but since
etermination of the OS formed, owing to its small concentration,
nvolves formidable technical difficulties, we must try to find a
easonably representative part of the OS that is easy to handle
nalytically. The weight of DS might be used for this purpose were
t not for the fact that the highly variable proportion of skeletal

material and of inorganic mineralization products, even in the ocea might give a distorted picture. And determinations of organic and P are too difficult for long series of experiments on board shi

The writer has developed a technique for determining protein small aqueous samples. This technique, which has often proved value in serial analyses, will detect small amounts of protein dow to 10 μg (*cf.* Krey, *et al.*, 1957). Major objection to this procedu may be raised on the grounds that a variable proportion of the C is shown by this protein determination, which yields only a s called albumin equivalent, standardized on albumin. Actually, suc objection applies to any component determination, but since th OS formed cannot be ascertained directly, it is better to determi one of its most representative parts than to forego all quantitati investigation.

As a fundamental property of protoplasm, plankton protein responsible for the economy of matter and energy in plankton. knowing the specific exchange factor, the mineralization output ma be computed. This seems particularly attractive today, now tha the O_2 and especially the ^{14}C technique have made the assimilatio output of plankton determinable.

In the following pages, attention will also be devoted to the pr portion of albumin nitrogen in ΣN ,calculated from the album equivalent by means of the protein factor 6.25. One might suppo *a priori* that this value would be substantially below the ΣN valu themselves, since these include not only nitrogenous skeletal sub stances but also the biochemical predecessors, intermediaries an decay products of protein metabolism. It is also possible that th dissolving process in the biuret determination breaks down a po tion of the protein too far. From previous studies, however, we ma conclude that this portion is small (Krey, 1951).

Determination of the albumin equivalent, therefore, affords possibility of determining the stock and of arriving indirectly at statement about its biological activity.

Specimen Material and Analytical Procedure. Excepting sample from the waters north of Iceland, net plankton from Kiel Ba particularly the outer part, was used exclusively. Generally Müll Nos. 12 and 18 meshes were preferred to the finer No. 20 to elimina so far as was possible the fine detritus. The catch was usually draine on a folded filter for one to three hours. The residue was carefull

ken up with a horn spoon to avoid contamination by paper fibers.
n some cases, this mass was freed from adhering interstitial water
W) by repeated application of dry filter paper until the mass was
rm. The resulting material, approximately "live weight," was re-
uced to dry weight in a porcelain dish for 12 hours at 110° (DS).
he difference of these two weights gave the water content. The
S was determined after Postma (1954) by calcining the material
a porcelain crucible at red heat and then determining the carbon-
e titration value. Analyses for ΣN by the Kjeldahl method to
accuracy within 0.1 $^0/_0$ were performed by Dr. Hans Kay (Che-
sches Institut der Bundesforschungsanstalt für Milchwirtschaft in
el), to whom I should like to make cordial acknowledgment here.
he albumin equivalents were determined by the modified biuret
chnique, likewise accurate within 0.1 $^0/_0$ (Krey, *et al.*, 1957).

Microscopic examination of the plankton is especially valuable
nd necessary for a meaningful breakdown of results of the 23 anal-
ses. The percentages, by volume, of plankton groups observed are
timates. Table I summarizes these observations.

When the volume of a sample clearly consisted of more than
5 $^0/_0$ of one of the main groups, the sample was then assigned to
e appropriate group. All other samples were listed as mixed
ankton, which normally would occur most commonly in nature;
ere, however, they are placed in a residual category since this
ries of analyses was directed primarily at chemical description
f the main groups, and the collection of plankton was organized
ith that in mind.

Water Content of Fresh Plankton. The water content of some
mples was determined as described above. The procedure used
n hardly be considered entirely satisfactory, but nevertheless
e values found were fairly consistent, except for sample 17; here
e water content was unusually low although the remnants of
dividual *Pleurobrachia* present should have resulted in a higher
ater content than was obtained. The average for nine samples may
computed at 11.5 $^0/_0$ DS. Laevastu (1957: tables 3, 4), in a recent
bulation from the works of other authors, has cited an average
12 $^0/_0$ DS for total plankton, with 11 $^0/_0$ for diatoms and 6 $^0/_0$
r peridiniales. Our findings are given in Table II.

Organic Content. Analyses of marine plankton for organic content
n yield no more than approximate values, whether interstitial

TABLE I. Microscopic Identification of Samples, with Notes on Process

No.	*Sample Date*	*Place*	*Main Components*	*Comments*
A) Diatoms				
3	—/VII/50	*	Diatoms (99 $^{0}/_{0}$)	With IW; kept 7 yrs wi excluded
19a	15/III/57	+	Diatoms (95 $^{0}/_{0}$) Dinoflagellates (3 $^{0}/_{0}$)	Without IW
19b	15/III/57	+	Same as 19a	Same as 19a, but after in aerated water.
20	20/III/57	+	Diatoms (95 $^{0}/_{0}$) Ceratia (2 $^{0}/_{0}$) Zooplankton (3 $^{0}/_{0}$)	20 hrs old; without IW.
21	26/III/57	+	Diatoms (85 $^{0}/_{0}$) Ceratia (5 $^{0}/_{0}$) Zooplankton (5 $^{0}/_{0}$)	Without IW.
22	4/IV/57	+	Diatoms (95 $^{0}/_{0}$) Ceratia (1 $^{0}/_{0}$) Zooplankton (2 $^{0}/_{0}$)	Same as 21.
B) Ceratia				
7	6/XI/56	+	*Ceratium* sp. (99 $^{0}/_{0}$)	Fresh material immed washed twice with dist. and filtered.
8	12/XI/56	+	*Ceratium tripos* (95 $^{0}/_{0}$)	With IW.
9	22/XI/56	+	*Ceratium tripos* (80 $^{0}/_{0}$)	Washed on ship with dist. and heated to about filtered on paper after 3 hrs.
14a	15/I/57	++	*Ceratium tripos* (90 $^{0}/_{0}$) Copepods (8 $^{0}/_{0}$)	Dead material; filtered 20 hrs after collecting washed; without IW.
14b	15/I/57	++	Same as 14a	Same as 14a, but with
15a	23/I/57	*	*Ceratium tripos* (80 $^{0}/_{0}$) Copepods (15 $^{0}/_{0}$) Diatoms (2 $^{0}/_{0}$)	Without IW.
15b	23/I/57	*	Same as 15a, but with some *Pleurobrachia*	With IW.
16	21/II/57	+	*Ceratium tripos* (90 $^{0}/_{0}$) Copepods (5 $^{0}/_{0}$) *Sagitta* sp. (2 $^{0}/_{0}$)	Without IW.

* Kieler Innenförde. + Kieler Förde. ++ Boknis Eck.

TABLE I (continued).

Sample Date	Place	Main Components	Comments
PEPODS			
--/VIII/48	**	*C. finmarchicus* (100 $^0/_0$)	With IW; much fat.
--/VI/56	+	Copepods (99 $^0/_0$)	Little fat; washed with tap water.
--/VII/56	+	Copepods (98 $^0/_0$) Mollusc larva (1 $^0/_0$)	With IW.
6/XII/56	*	Copepods (80 $^0/_0$), with *Sagitta* sp., polychaete larvae	Without IW.
ED PLANKTON			
4/XII/56	*	*Ceratium tripos* (50 $^0/_0$) Copepods (45 $^0/_0$), polychaete larvae, *Sagitta* sp., shellfish larvae, copepod eggs, *Oikopleura*	With IW.
6/XII/56	*	Copepods and *Sagitta* sp. (80 $^0/_0$), polychaete larvae, diatoms	Same as 11a, but bottom portion only.
8/I/57	*	*Ceratium tripos* (50 $^0/_0$), *Sagitta* sp. (20 $^0/_0$), Polychaetes (10 $^0/_0$), Copepods (5 $^0/_0$)	With IW.
1/III/57	+	*C. tripos* (50 $^0/_0$), Diatoms (20 $^0/_0$), Copepods (25 $^0/_0$), polychaete larvae, some *Pleurobrachia*	Without IW.
6/III/57	+	Diatoms (*Skeletonema*) (75 $^0/_0$), *C. tripos* (15 $^0/_0$), Copepods (5 $^0/_0$)	Without IW.

ler Innenförde. + Kieler Förde. + + Boknis Eck. ** N. Iceland.

ter is drawn off or not. If the saline IW is not drawn off, the ash lues obtained will be too high. Assuming, for example, that a sh sample of plankton holds only 10 $^0/_0$ IW and that the water s an initial salt content of only 20 $^0/_{00}$, then this alone will account r 0.2 $^0/_0$ of the DS as ash upon calcining. On the other hand, live

TABLE II. DRY SUBSTANCE IN NET SAMPLES

	Diatoms				*Ceratia*			*Copepods*	*Mixed Plankton*	
mple No.	19a	20	21	22	14a	15a	16	11a	17	18
DS	11.0	14.7	11.1	7.0	11.5	10.3	13.0	13.6	21.1	11.0
erages	11.0				11.6			—	—	

plankton certainly loses major amounts of dissolved or finely persed OS during filtration. Thus, while removal of IW by suct will diminish the ash content, OS in unascertainable amounts also be removed at the same time.

In Table III the values for OS are clearly differentiated am the several groups of organisms. The diatom samples, as expect show values between 36.2 and 62.0 $^0/_0$ OS on DS as against 71.5 95.4 $^0/_0$ for Ceratia and 88.8 to 93.6 $^0/_0$ for copepods. If sam without IW as well as the washed samples are omitted, the foll ing picture is obtained:

	Diatoms	*Ceratia*	*Copopods*	*Mi Plan*
Sample No.	3, 21, 22	8, 14 b, 15 b	4, 6	10,
$^0/_0$ OS on DS	36.2–62.0	71.5–86.8	90.2–93.6	85.4–
Average	52.9	80.8	91·9	87.
Aver., all samples	53.7	84.7	91.5	78.

Although it cannot be claimed that this tabulation is gener valid in view of the small body of data and the above-mentio fundamental difficulties, it does serve to show–in conjunction w analyses by other authors–the great difference between diato on the one hand and Ceratia and copepods on the other. Note t the average of all samples for a certain group is sometimes lo and sometimes higher than that of selected samples. This is plained by the fact that the material has considerable natu variation and that the number of samples is small.

In recent publications, Laevastu (1957:25) has given the foll ing averages in his tabulation of analyses by other workers: diato 55 $^0/_0$ OS; peridinians, 80 $^0/_0$ OS; zooplankton, 88 $^0/_0$ OS. The C mittee on Terms and Equivalents of the 1957 Plankton Symposi put the OS content of phytoplankton at 69 $^0/_0$ and that of z plankton "close to 100 $^0/_0$." Vinogradov (1953), from studies Hensen and Brandt and from his own original research, compu a content of 41.6 $^0/_0$ OS for diatoms. Vinogradov's own studies *Rhizosolenia calcar-avis* from the Caspian Sea show an average 50.2 $^0/_0$ OS, but he also obtained values of 40 $^0/_0$.

On the whole, the organic content in diatoms varies more wid than that in other groups, as might be expected from the dive nutrition and from the structure of the siliceous skeleton. Laevast erages may stand, so far as our analyses are concerned, pending cumulation of more extensive data based on seasonal differences plankton composition.

TABLE III. CHEMICAL COMPOSITION OF PLANKTON SAMPLES

Sample No.		*Main Component (microscopy)* (%)	*In 100 mg DS:* *OS* (*mg*)	*ΣN* (*mg*)	*Alb.Eq.* (*mg*)	*In 100 mg OS:* *N* (*mg*)	*Album. Equiv.* (*mg*)	*= % of ΣN*
DIATOMS								
3		Diatoms (99)	62.0	2.86	14.2	4.6	22.9	79.4
19a	*	Diatoms (95)	57.5	2.37	8.4	4.1	14.6	57.0
19b	*	Diatoms (95)	53.6	2.51	7.7	4.7	14.4	49.0
20	*	Diatoms (95)	52.3	2.84	8.1	5.4	15.5	45.8
21		Diatoms (85)	60.6	4.71	16.2	7.8	26.6	55.0
22		Diatoms (95)	36.2	2.59	10.3	7.2	28.5	63.7
CERATIA								
7	+	Ceratia (99)	86.4	3.94	20.9	4.6	24.2	85.0
8		Ceratia (95)	84.0	4.13	19.0	4.9	22.6	73.6
9	+	Ceratia (80)	95.4	4.30	18.3	7.4	24.5	68.2
14a	*	Ceratia (90)	77.5	3.22	13.7	4.2	17.7	68.1
14b		Ceratia (90)	71.5	3.10	17.4	4.3	24.3	90.0
15a	*	Ceratia (80)	87.4	4.53	16.0	5.2	18.3	56.5
15b		Ceratia (80)	86.8	5.28	19.9	6.1	22.9	60.4
16	*	Ceratia (90)	88.8	4.81	17.4	5.4	19.6	57.8
COPEPODS								
4		*Calanus* sp. (100)	93.6	7.03	20.9	7.5	22.3	47.7
5	+	Copepods (99)	93.4	10.4	48.1	11.1	51.6	74.0
6		Copepods (98)	90.2	9.22	38.0	10.2	42.2	66.0
11a	*	Copepods (80)	88.8	7.18	29.2	8.1	32.9	65.0
MIXED PLANKTON								
10		Ceratia (50) Copepods (45)	85.4	6.35	20.9	7.4	24.5	52.8
11b	*	Copepods (<80) Ceratia (?) Diatoms (?)	81.5	5.84	18.5	7.2	22.7	50.7
13		Ceratia (50)	89.8	5.34	20.9	5.9	23.3	62.8
17	*	Ceratia (50)	70.0	4.73	18.1	6.8	25.9	61.3
18	*	Diatoms (75)	64.3	4.19	16.6	6.5	25.8	63.5

Without interstitial water

Washed samples

Total Nitrogen. Since the DS contains a highly variable proporti of ash, the OS must be taken as a point of reference for further c culations in order to ascertain not only the net product of metabo processes in the sea but the potential biological activity as we Although total nitrogen, ΣN, has usually been chosen to represe protein content, this procedure involves both methodological a technical difficulties that prevent its general application to t problems of production biology.

The first fundamental analyses for ΣN were performed by Bran and Raben (1922), their values being referred to ash-free DS, what we are here calling organic substance:

	Diatoms	*Peridinians*	*Copepod*
Number of analyses	8	8	2
Extreme values of N, $^0/_0$ of OS	6.82–12.92	7.87–11.93	11.81–12
Averages	10.4	10.4	12.2

Their specimens, excepting the copepods taken in the North S were from Kiel Bay.

Our own ΣN values, given in Table III and recalculated on t basis of OS, are almost all lower than those found by Brandt a Raben. Our averages are:

	Diatoms	*Ceratia*	*Copepods*	*Mix Plank*
ΣN, $^0/_0$ of OS	5,6	5.0	9.2	6.8
Extreme values	4.1–7.8	4.2–7.4	7.5–11.1	6.5–

These values also scatter considerably; thus, in the case of d toms, the minimum is only 40 $^0/_0$ of the maximum (correspondi to Brandt's 53 $^0/_0$). The wide differences between these two ser of determinations cannot be due entirely to dissimilar qualitati composition of the material; analytical procedure may have be responsible for part of the wide discrepancy.

In addition to Brandt and Raben's analyses, there are a num of ΣN determinations in the literature, a few of which are giv here for comparison:

		Av. $^0/_0$ *N*
) DIATOMS		
Vinogradov (1939)	*Rhizosolenia calcar-avis**	11.0
Harris and Riley (1956)	Coscinodiscus	11.0
Harris and Riley (1956)	Total phytoplankton	4.5
) DINOFLAGELLATES		
Harris and Riley (1956)	*Goniaulax*	5.6
Vinogradov (1953)	Average	5.6
) COPEPODS		
Marshall, *et al.* (1933)	*Calanus finmarchicus*	8.0
Comm. Terms and Equiv. (1957)	Zooplankton	11

* Eight determinations.

While agreement of these with our values is satisfactory, it is ardly possible to adopt one fixed percentage for all groups; it is bvious that a particular ΣN content will have to be based on the articular plankton group that is dominant at one time of the year r another. Again we see the need for seasonal analyses of the various roups, but until they are available we must content ourselves with entative averages (given in $^0/_0$ N on OS) determined from available analyses:

	$^0/_0$ *N on OS*	
iatoms	6.9	(23 values)
eridinales	7.6	(17 values)
alanus finmarchicus	8.0	(117 values; Marshall, *et al.*)

Albumin Equivalent. As discussed previously, the albumin equivalent should represent more strictly the active biotic mass proper han the N content. One would also expect that this proportion of S would be subject to much the same fluctuations as the ΣN content and that the N content computed from the albumin equivalent ould be smaller than ΣN.

The values of the albumin equivalent – referred to OS as before – Table III confirm these expectations. For diatoms and Ceratia e find albumin equivalents of 20.4 and 21.8 $^0/_0$ respectively, for ixed plankton 24.4 $^0/_0$, and for copepods 37.3 $^0/_0$. In previous work have reckoned with an average protein content of 40 $^0/_0$, but in e samples considered here this level is reached only twice – for pepods. From the N analyses we might arrive at 43 $^0/_0$ albumin r diatoms, 48 $^0/_0$ for Ceratia, and 50 $^0/_0$ for copepods, if we mul-

tiply by the factor 6.25. However, according to present analys
and until more analytical data are available it will be necessary
assume an average of 21 $^0/_0$ for phytoplankton and 24.7 $^0/_0$ for to
plankton on OS.

Considering individual groups, variations in the equivalent alb
min content are greatest among diatoms and least among mix
plankton. The wide scatter among copepods is not unexpected, sin
these, to an even greater degree than diatoms, have variable reser
materials. In copepods, for example, the minimum albumin eq
valent is fully 57 $^0/_0$ of the maximum, whereas the correspondi
relationship for ΣN gives 35 $^0/_0$. This scatter must be caused
the biochemical behavior of nitrogen, to be discussed in the ne
section.

Analyses show that a highly variable proportion of ΣN is re
resented in the albumin equivalent, which, if divided by the custo
ary protein factor of 6.25, gives the N corresponding to our bio
mass proper. This N is referred to ΣN in the last column of Table I
We see at once that there is no case in which even 95 $^0/_0$ of ΣN
included in albumin N. The values range from 54.8 to 90 $^0/_0$, wi
an average of 62.3 $^0/_0$ for 23 analyses. Further biochemical inves
gations are required to ascertain how the residual N is fixed, a
analyses for this purpose on dry material of our samples have be
undertaken in collaboration with Prof. Dr. Fritz Bramstedt
Hamburg.

Parallel Samples. To what extent the treatment of samples m
affect the analytical data remains to be determined. Initially
note that this treatment is within the scope of ordinary analyti
procedure; that is, deviations introduced are possible in any of t
other analyses also.

First let us see to what extent elimination of the IW may alt
the analyses. This question was examined on comparatively u
mixed samples of *Ceratium* (samples 14, 15). Sample 14 consist
of a catch that was aerated about 20 hours on board ship and
the laboratory aquarium before it was concentrated. By the ti
this material was filtered in the laboratory, it was already lifele
and numerous cells showed under the microscope the emergence
plasma. As comparison of the a and b samples shows, eliminati
of the water results in a decreased ash content. The ΣN conte
referred to OS, remains about the same while the albumin equiv

nt falls. It appears, then, that if elimination of IW removed the truded plasma as well, the ΣN content should have declined also.

In sample 15 a similar analysis was carried out with fresh material. ere, after elimination of IW, there was only a slight drop in OS, t, as in sample 14, there was a considerable drop in the albumin uivalent–paralleled, as expected, by a drop in the ΣN value.

The effect of keeping material for 24 hours in an aerated aquarium as investigated with pure diatomaceous material from sample 15. e OS content fell, probably owing to respiration, the albumin uivalent in OS remained unchanged at $14.4\,^0/_0$, and N rose by out $15\,^0/_0$ of its initial value. Here there is a possibility of re- ation of N in a loose binding.

Finally, an analysis was made to determine whether or not visual paration into several layers in apparently homogeneous copepod aterial was verifiable chemically. Sample 11 consisted of a large oportion of copepods and a small proportion of diatoms, with the a sample representing the top portion and the 11b sample the ttom portion. Separate analysis of these a and b portions showed at the lower portion contained more ash than the upper portion, ssibly because of diatom sediment, as is indicated also by the wer N content and lower albumin equivalent in OS. This means at sample 11b also belongs in the category of mixed plankton.

These comparisons of the treatment of net samples before analysis ggest the following procedure in future studies:

1) Processing as promptly as possible to avoid loss of tissue fluids nd loss of OS through respiration.

2) Suction filtration of IW in determining the OS content of DS. nce extruded protoplasm is removed with the water, a parallel nalysis should be run without removing the IW.

3) Samples with an abundance of highly motile zooplankton in ddition to diatoms should either be subjected to visual separation efore further concentration or be assigned to the mixed plankton.

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THE OCCURRENCE OF PIGMENTS IN MARINE SEDIMENTS[1]

By

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ABSTRACT

Qualitative and quantitative studies of pigments in marine sediments, using romatographic and spectrophotometric methods, showed the presence of dedation products of chlorophylls; some of their optical properties are given. It concluded that pigments decompose rapidly in aerated, coarse-grained sediment ereas in deeper layers of the same sediment, under anaerobic conditions, decomsition is slow. It is suggested that the decreasing amount of pigment with ineasing depth of sediment can be used as a criterion for determining the past enronmental conditions of deposition.

INTRODUCTION

According to Neaverson (1940), it is probably chlorophyll which ives the greenish color to some marine sediments; he noted that isible chlorophyll grains in marine sediments became brownish in lor upon oxidation and decomposition.

Investigations of Motovskij Bay by Gorschkova (1938) showed at organic substance in shallow water sediment was richer in lorophyll than that from deep water sediment; quantitative eterminations by him gave the following results: organic carbon shallow water 1–2 $^0/_0$, in deep water 1.3–2.8 $^0/_0$; chlorophyll in allow water 0.0014–0.0037 $^0/_0$, in deep water 0.0008–0.0023 $^0/_0$. lenova and Jastrebova (1938), who found 0.6–3.74 mg chlorophyll

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in 100 g fine fraction of sediment from the Caspian Sea, stated th
chlorophylls are best preserved in anaerobic conditions.

Jastrebova (1938) recorded the presence of chlorophyll in o
burning shales from the Upper Jura. From chlorophyll determin
tions in sediments from the Barents Sea and from laboratory e
periments on conditions of preservation of chlorophylls in sediment
Jastrebova concluded that chlorophylls are well preserved by fi
muds but are quickly oxidized in sandy sediments. A correlati
was found between the amount of fine grain-size fraction and t
amount of chlorophyll present in surface sediment. The mean val
of chlorophyll in surface sediment from the Barents Sea was 0.75 m
in 100 g dry sediment; from the Kola Fjord it was 0.5–5.7 mg
100 g sediment without fraction greater than 1.0 mm. Furthermor
Jastrebova suggested that the amount of chlorophyll in the sed
ment surface and its relation to organic substance gives a measu
for the rate of ventilation of surface sediment and that the rate
progressive decrease of chlorophylls in sediment can be used as
measure to determine the rate of sedimentation.

Fox and Anderson (1941), in a spectrographic study of pigmen
in sediment, found no chlorophylls, but they did find several gree
compounds which they believed to be decomposition products
chlorophylls. Vallentyne (1955, 1957) concluded that the gree
pigments occurring in sediments are sedimentary chlorophyll d
gradation products (SCDP) rather than chlorophylls, and that u
doubtedly the green lipoidal substances of sediments were forme
from plant chlorophylls. Vallentyne (1957) has provided a sho
summary of previous works on pigments found in sediments. O
and Grady (1957) found 4 to 100 ppm of chlorophyll derivates, ca
culated as pheophytin *a*, in surface sediment samples from mari
basins off southern California, and Gillbricht (1952) reported th
the amount of chlorophyll in dead detritus in sea water was fo
times that in living plankton.

In the present study an attempt has been made to give a quant
tative picture of the pigments present in sediments of the San Jua
Archipelago. The nature of pigments and some of their optical pro
erties as well as their condition of preservation in relation to sed
ment depth have been investigated.

METHODS

Separation and identification of various pigment components was de chromatographically with combined absorption columns after e procedures given by Strain (1945) and by Zechmeister and olnoky (1941). In the separation process, the following absorbts were used: (a) powdered sugar for chlorophyll *a* and *b*; (b) gnesium carbonate for protochlorophylls; (c) calcium carbonate xanthophylls; (d) dialuminium trioxyd for carotenes. Ethanol, thanol, acetone, petroleum ether and benzene were used as solnts and chromatogram developers.

Since pigments oxidize rapidly when in contact with air, the sedint samples were taken from the cores as quickly as possible and pt in tightly-packed, air-tight tubes. The sediment was then dried vacuum over a diluted sulphuric acid that gave a vapor pressure rresponding to 60 % saturation pressure at 20° C (laboratory nditions).

The method developed by Richards with Thompson (1952) for multaneous quantitative determination of different chlorophylls d carotenoids in marine plankton was followed to a great extent the quantitative investigations. 0.5–1 g air-dried sediment was ached for 18 hours with a given amount (5–10 ml) of 90 % acetone; e suspension was shaken several times during this period. The mples were then centrifuged and the optical densities of the relting acetone solution were measured with a Beckman DU Spectrootometer.

By chromatographic separations, chlorophylls were found in only ace amounts in the surface layers of sediment. The pigment comounds were assumed to be mainly the hydration and oxidation oducts of chlorophylls, but the specific absorption coefficients of ese hydration products are not known. The quantities of pigment ve therefore been reported in pigment units (PU), following ichards with Thompson's computation. In most cases, only the uivalent *a* component has been computed. Assuming that the ecific absorption coefficient of the green pigments found in sedient is close to the specific absorption coefficients of chlorophylls, e PU approximates one μg pigment.

Estimation of organic carbon in sediments was made by Shollenrg's method with Allison's (1935) modification. This method is also described and used by el Wakeel and Riley (1957) for det mination of organic carbon in marine muds.

STUDY MATERIAL

Short sediment cores were collected with a gravity corer fro different environmental conditions in the San Juan Archipela Two of these (Cores 1 and 2) were taken from East Sound whe water layers are fairly stable during most of the year. Organic p duction is also greater there than in any other locality of the ar and the water has a low dissolved oxygen content close to the b tom. The sediments are rich in organic matter because little deco position of organic matter takes place on sediment surface. T color of these sediments is greenish-black to greenish-grey and th often smell of hydrogen sulfide.

Cores 3–9, taken from other localities of the San Juan Arc pelago where the bottom water has a high dissolved oxygen conte varied greatly from place to place, according to the depth of wat and the strength of tidal currents near the bottom. These cor consisted of coarse sand, small amounts of organic matter and c careous shell fragments.

Nature and Optical Properties of Pigments in Sediments. The pi ments were easily soluble in 90 $^0/_0$ acetone, and the resulting soluti was brownish-green. They were also easily soluble in ethanol a methanol, but with a less intense and much greener color than th from acetone. The pigments were only slightly soluble in benzen which gave a pale brownish-green solution. Petroleum ether h practically no effect on the pigments and the solution was color only a light bluish-green.

Except for indications of traces in the uppermost layers of t sediment, no chlorophylls were found by chromatographic separatio a finding which corresponds with results of Fox and Anders (1941). One of the most common pigments found by these autho had the wavelength of maximum absorbency in petroleum ether 669 mμ. According to Orr and Grady (1957), pheophytin *a* giv absorption maxima in chloroform at 668 mμ. The absorption spect of the 90 $^0/_0$ acetone solutions of the sediments are given in Fig.

In general, these absorption spectra are somewhat similar those found in plankton extracts (Richards, 1952). However, the so show some characteristics similar to the absorption spectra of eophytin *a* (Orr and Grady, 1957). In this study the wavelength maximum absorbency of pigments from a sediment surface layer s about 667 mμ, which possibly indicates the presence of chloroyll, found in traces by chromatographic separation of these sedi-

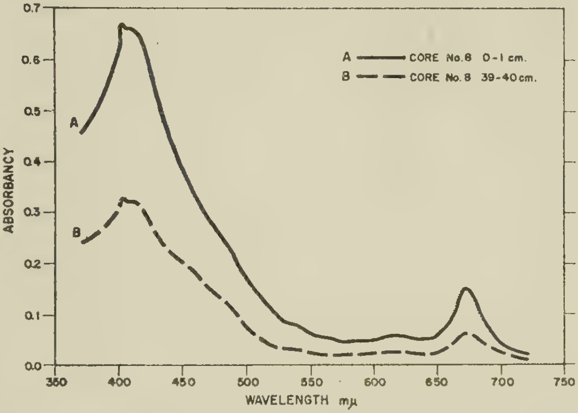

Figure 1. Absorption spectra of 90 % acetone solutions of sediments.

ents. In more oxidized sediments and especially in layers at depth, e wavelength of maximum absorbency is 670–672 mμ. The other ak of maximum absorbency of 608 mμ shows the same tendency move towards the longer wavelength in more oxidized sediments. Peaks of 480 and 510 mμ indicate the presence of carotenoids, t these peaks are also present to some extent in pheophytin *a*. ecause of the great similarity of optical properties of chlorophyll *a* d its degradation products, it is assumed that the chlorophylls und by Russian workers represent in reality the same degradation roducts as those found by Fox and Anderson (1941), Vallentyne 955), Orr and Grady (1957) and in the present work.

Quantitative Occurrence of Pigments in Sediments. Using the formae of Richards with Thompson (1952), only the chlorophyll *a* mponent was calculated; in Table I this is represented as pigment pigment units (PU). Cores 1 and 2, taken from anaerobic contions in East Sound, had a high content of both organic carbon d pigments which did not become less with depth. This probably dicates that no decomposition of organic matter takes place in

TABLE I. ORGANIC CARBON AND GREEN PIGMENTS IN THE SEDIMENTS FROM S
JUAN ARCHIPELAGO

Core No.	*Locality, Character of Sediment, and Depth of Water*	*Sediment Depth (cm)*	*Organic Carbon (°/₀)*	*Pigments P.U. in Dry Sedim*
1	East Sound	0.5– 2	3.16	115
	Greenish black mud; smells of H_2S	4– 6	3.28	125
	Depth 22 m	9–11	3.12	130
		14–16	3.14	110
		19–21	3.28	135
		22–24.5	3.01	130
2	As above	0.5–2		105
	Depth 27 m	4– 6	3.30	65
		9–11		95
		14–16	2.84	100
		19–21	3.11	75
		23–24.5	2.90	100
3	Composite sample, S. Juan Channel			
	Dark gray sandy mud			
	Depth 50–100 m	0– 5	1.76	31
4	George Pt., Shaw Is.	0– 1	2.22	19
	Black sandy mud	9–10	1.81	12
	Depth ca. 120 m	15–16	1.38	10
5	George Pt., Shaw Is.	0– 1	2.12	17
	Dark gray sand and shells	13–14	0.87	3
	Depth ca. 120 m			
6	NE of Brown Island	0– 1	1.60	15
	Gray sand and shells	10–11	0.74	4
	Depth 50 m			
7	Lopez Sound	0– 1	1.52	61
	Fine sandy mud	4– 5	1.66	22
	Depth 42 m	9–10	1.10	10.5
		14–15	2.50	19.5
		19–20	2.41	18.5
		24–25	2.49	18.0
		29–30	2.48	19.0
		34–35	2.59	17.5

TABLE I (continued).

Core No.	*Locality, Character of Sediment, and Depth of Water*	*Sediment Depth (cm)*	*Organic Carbon (%)*	*Pigments in P.U. in 1 g Dry Sediment*
8	Off Friday Harbor	0– 1	0.91	16.5
	Gray sandy mud	4– 5	0.75	10.5
	Depth 17 m	9–10	0.98	8
		14–15	1.40	5.5
		19–20	1.19	4.5
		24–25	1.36	6.5
		29–30	1.40	8
		34–35	1.03	7.5
		39–40	0.91	8
9	Off Friday Harbor	0– 1	1.06	21
	Coarse gray sandy mud with shells	4– 5	1.12	14
	Depth 34 m	9–10	1.08	10.5
		14–15	0.91	6
		19–20	0.90	3

the sediment in this anaerobic environment. Core 1, from shallow water, had more pigments per unit amount of organic matter than Core 2. This also indicates that the degeneration of organic matter takes place essentially while sinking in the water, before it reaches the anaerobic bottom. The mean pigment content of 1 g organic matter was about 2 mg or 0.2 %, assuming that 1 PU equals 1 μg pigment.

A combined sample of surface sediment (designated as Core 3) from San Juan Channel showed 3.2 % organic matter (org C × 1.8), in which only 0.1 % pigment was present. By comparison, the chlorophyll content of dry plankton has been estimated as 2.9 % by Riley (1946). Cores 4 through 9 showed varying amounts of organic carbon and pigments, the amount of pigment in relation to organic matter apparently being dependent on the texture of the sediment. The pigments decreased rather rapidly in the uppermost 10–15 cm, but showed little decomposition (Fig. 2) and reducing conditions in the deeper sediment layers. The above findings also show that pigments cannot be used either as an indicator for the amount of organic matter in the sediments or as a measure for the rate of sedimentation.

However, the amount of pigment in relation to the amount of organic matter and the decrease in the amount of pigment with depth of sediment can be used as criteria for determining conditions of deposition and decomposition of sediments. In coarse sediment and in places where the water above the sediments is high in dissolved oxygen, decomposition of pigments is rather rapid. On the other hand, in deep water, pigments decompose to a great extent in the water mass before reaching the sediment, hence the amount of pigment and organic matter is less in deep water sediments than in shallow water sediments by the same basic organic production in the water mass above the sediment. Therefore, consolidated sediments containing pigments must have been deposited in relatively shallow and badly aerated or euxinic waters.

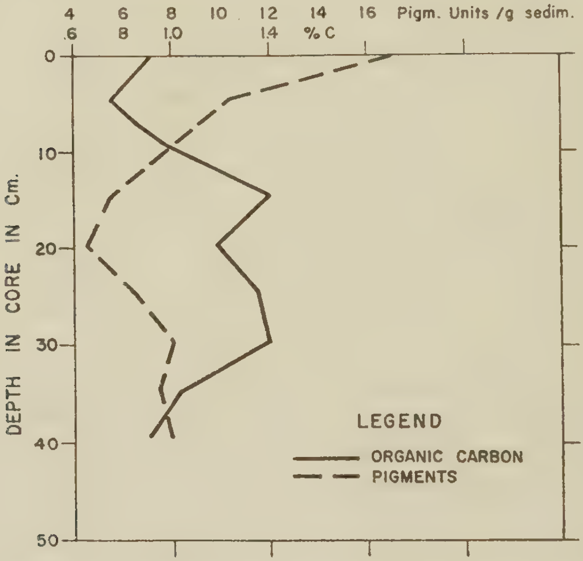

Figure 2. Distribution of pigments and organic carbon at different depths of sediment in Core 8.

There are enough pigments in shallow water sediments to give them the characteristic greenish or bluish color. Upon oxidation (f. i., ignition) of these sediments, the brownish or reddish-brown color is attributed to higher amounts of iron and manganese oxides.

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SUMMARY

1. The absorption spectrum of pigments from sediments in 90 % etone solution is given in Fig. 1. The peaks of maximum absorp- n shift toward the greater wavelengths with advancing oxidation nd decomposition of pigments.

2. In coarse and well-aerated sediments the pigments decompose pidly. In fine sediments, and especially in sediments from anae- bic conditions, the pigments are relatively stable.

3. Although the amount of pigment and its decrease within the epth of sediment cannot be used as an indication of the amount organic matter or as a measure of the rate of deposition, it may e used as a criterion for the environment of deposition.

4. The green pigments are the coloring compounds of shallow water ediments.

5. The organic matter in the sediment surface in San Juan Archi- elago contains 0.1–0.2 % pigments.

6. Below 10–15 cm of the sediment surface, reducing conditions revailed in most coastal sediments.

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NEW METHOD FOR DIRECT DETERMINATION OF SALINITY

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ABSTRACT

The solid material obtained upon freeze-drying sea water is not a true measure salinity since it contains 9 or 10 $^0/_0$ water of crystallization, the exact content ing a sensitive function of temperature and humidity. The residual water is deterinable with Karl Fischer reagent, although the method is not yet capable of yieldg salinity with the precision hitherto obtainable through the Knudsen titration. otal salt (Σ'), found by freeze-drying and determining residual water with Karl ischer reagent, is the proportion of solid material when all of the bicarbonate is hydrated at the rate of one water molecule per bicarbonate molecule and when e boric acid is dehydrated at the rate of three water molecules per boric acid olecule; however, the fate of the organic matter is uncertain. Neglecting organic atter, the theoretical ratio of Σ' to S for ordinary oceanic chlorinities should be out 1.0028, compared with the ratio Σ to S of 1.0046 found by Lyman and Fleming.

INTRODUCTION

In the course of investigations of water metabolism at the Walter eed Army Institute of Research (Wolf, 1958), it became necessary devise procedures for determination of the water and solid connts of various fluids. In many cases, evaporation to dryness at w temperatures proved to be a satisfactory method for this purose, the loss in weight being considered water and the remaining lid material solute.

In the case of sea water, however, where the classical Knudsen-ohr titration provided an accurate check on the amount of solid

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material, results were not wholly satisfactory. Thus when a seri
of samples was freeze-dried simultaneously, the values for total sol
were very closely proportional to the chlorinities derived fro
titration, but there were large variations in the constant of propo
tionality between different series, the constant always being sign
icantly greater than the value 1.8110 derived by Lyman and Fle
ing (1940). It appears from these results that sea salts hold wat
of crystallization and that the exact water content of these sol
salts is a rather sensitive function of temperature and vapor pre
sure, which are not easily controlled during the drying proce
A method was therefore sought which could determine the wat
of crystallization without leading to hydrolysis of $MgCl_2$ and MgB
and the consequent loss of HCl and HBr. Karl Fischer Reage
(KFR, a methanol solution of iodine, sulfur dioxide, and pyridin
proved satisfactory for this purpose, since the values for water
crystallization, when subtracted from the original weights of sol
material, left differences which were in satisfactory agreement wi
values of total solid calculated from the Knudsen titration.

Karl Fischer reagent may produce water chemically throu
reactions involving its methanol. Mitchell and Smith (1948) ha
described in detail such reactions with various compounds, two
which (bicarbonate and boric acid) are naturally present in s
water. An experiment was accordingly set up to determine the e
tent to which these two substances may interfere with the dete
mination of water in sea salt residues and to ascertain the possib
usefulness of the freeze-drying/Karl Fischer reagent determinati
as an oceanographic tool.

METHODS

A 10-ml portion of sea water was delivered rapidly to a tar
50-ml glass-stoppered Erlenmeyer flask, which was then reweighe
Flasks and stoppers were oven-dried and stored in a desiccat
together with a supply of rubber caps and magnetic stirring ba
After the samples were frozen by partially immersing the flasks for
minutes in acetone-dry ice, the flasks were quickly wiped clean
excess frost, unstoppered, and placed in a vacuum desiccator ov
fresh $CaSO_4$ ("Drierite"). If a vacuum of about 300 μ Hg was reach
quickly, the samples remained frozen, with no foaming or spatterin
Once the bulk of the water had been removed, a vacuum of 50 μ
or less was maintained for 24 hours. The stoppers were then quick

placed and the flasks were again weighed. The loss in weight was nsidered to be entirely water, the residue to be salt plus water crystallization.

This remaining water was titrated with Karl Fischer reagent tabilized solution, Hartmen-Leddon Co., Philadelphia, No. 3786), hich reacts with water to reduce iodine to iodide, thereby de-lorizing the reddish-brown solution. To exclude atmospheric water ring the titrations, stirring was done magnetically and the glass ppers were replaced with rubber caps (Davol Rubber Co., Sani-b cap). Burettes were fitted with hypodermic needle tips which nctured the caps, and with these thick caps a good seal resulted en the needle was withdrawn. Before titration, 10 ml of anhy-ous methanol was added as a diluent and dispersant. During the pid addition of methanol or titrant, venting was provided by serting a # 25 needle through the rubber cap. This fine second edle was removed as the end point was approached.

With sea salt residues the first end point tended to fade rather ickly. Arbitrarily the end point was chosen as a color that per-sted for two minutes. Since suspended insoluble materials some-hat obscure the end point, a potentiometric end point, which we ve not tried, might improve the precision.

A blank was run on 10 ml of the anhydrous methanol to deter-ine its water content as well as water that may have been ad-rbed on the inside of the flask. This blank was then subtracted om the burette reading of the samples.

The water equivalent of the KFR was determined by adding ap-roximately 100 mg of water with a syringe to a weighed flask con-ining 10 ml of anhydrous methanol, reweighing, and titrating to e same end point as the blank. Although there was considerable riability in the value so derived, it did not show any consistent end with time. The standardizations were repeated a number of nes for several days, and the average of 15, which had a standard ror of 0.9 $^0/_0$, was used for computation.

The sea water, a surface sample from the western North Atlantic, d been filtered upon collection and was subsequently stored in a lyethylene carboy. Its chlorinity, determined at the Hydrographic fice by the standard Knudsen titration, was 20.24 $^0/_{00}$, equivalent a salinity of 36.56 $^0/_{00}$ and to a total salt content Σ (as defined Lyman and Fleming, 1940) of 36.73 $^0/_{00}$. Added to two portions this water were 402 mg/l of H_3BO_3 and Na_2HCO_3, respectively.

TABLE I. OBSERVED VALUES OF SALT AND WATER CONTENT IN SEA WATER

Run	*Total Solids by Freeze-Drying,* Σ'' (‰)	*Water in Total Solids by Karl Fischer Reagent,* W (%)	*Total Solid Water-free Basis,* Σ' (‰)
Series 1. *Sea Water*			
1	40.70	9.22	36.94
2	40.59	9.08	36.90
3	40.61	9.26	36.85
4	40.31	8.96	36.70
5	40.31	8.96	36.70
6	40.57	9.47	36.73
7	40.64	10.04	36.56
8	40.45	9.54	36.59
Series 2. *Sea Water + 402 mg/l* H_3BO_3			
1	40.72	9.50	36.85
2	40.69	9.34	36.89
3	40.73	9.54	36.84
4	40.91	9.54	37.00
5	41.01	9.50	37.12
6	41.11	10.10	36.95
7	41.16	9.82	37.12
8	41.21	10.13	37.03
Series 3. *Sea Water + 402 mg/l* $NaHCO_3$			
1	40.93	9.52	37.03
2	40.98	9.55	37.07
3	40.96	9.60	37.03
4	41.14	9.45	37.25
5	40.96	9.28	37.16

TABLE II. AVERAGES AND STANDARD DEVIATIONS

Series	*Mean Total Solid on Freeze-drying* Σ''	σ	*Mean %* *Water* W	σ	*Mean Water-free, Solid,* Σ'	σ
1	40.52	.15	9.32	.36	36.74	.14
2	40.94	.21	9.68	.30	36.98	.11
3	40.99	.14	9.48	.12	37.11	.10

Check chlorinities run on these two samples after addition of th
extra solute showed no measurable change in chlorinity, indicatin
a negligible volume change on addition of these chlorine-free co
stituents. The results are given in Tables I and II.

DISCUSSION

As already mentioned, the water content of the solid material tained by freeze-drying is a complicated function of temperature d vapor pressure. Hence considerable variation is to be expected values of Σ'' (Table I). However, for aliquots of a given sample, high value of Σ'' should be accompanied by a correspondingly h value of W and the values of Σ' should show less spread (Table I). r Series 1 and 2, this is indeed the case, with standard errors of 5 and 0.21 in Σ'' reduced to 0.14 and 0.11 in Σ'. In the case of ies 3, the standard error in Σ'' is only 0.08, while the value 0 in Σ' is virtually the same as that in series 1 and 2.

These results can be illustrated further by deriving equations for in terms of W for the three series:

$$\begin{aligned}
\Sigma_1'' &= 36.74 + 0.406\ W_1 \qquad & \sigma_1 &= 0.12\\
\Sigma_2'' &= 36.98 + 0.409\ W_2 \qquad & \sigma_2 &= 0.09\\
\Sigma_3'' &= 37.11 + 0.409\ W_3 \qquad & \sigma_3 &= 0.08.
\end{aligned}$$

f course the constant term in each equation is the value of Σ', e proportion of salt when the water content is zero. The standard rors of Σ'' in these equations have somewhat smaller values than ose of Σ' in Table II.

Considering first the results for Σ'', we find that the recovery of lid material by freeze-drying from samples of Series 2 and 3 veraged 0.42 and 0.47 $^0/_{00}$ respectively more than that from Series 1. ince the actual addition of solid material in each case was 402 mg/l r 0.393 $^0/_{00}$, it appears that freeze-drying adequately accounted for e added material and that the volume change on its addition was fact negligible, as already inferred from the chlorinity titration.

Results for W, however, indicate that there was an increased ntent of water in the freeze-dried precipitates of Series 2 and 3; sults for Σ' bear out this conclusion. In Series 2, the additive as H_3BO_3, with three molecules of H_2O being derived from each olecule of H_3BO_3, according to eq. $H_3BO_3 + 3CH_3OH \rightarrow B(OCH_3)_3$ $3H_2O$ (Mitchell and Smith, 1948: 256). Thus, if there is no effect n the water of crystallization, 0.39 $^0/_{00}$ H_3BO_3 should produce .34 $^0/_{00}$ more water in the freeze-dried precipitate, or 0.83 $^0/_0$ of 1 $^0/_{00}$. The observed mean increase in W is 0.36 $^0/_0$, but in view of e magnitude of the standard errors of the measurements involved, e discrepancy is of little practical significance. The increase in total solid, Σ', should be 0.05 $^0/_{00}$; the observed value is 0.24 $^0/$ the discrepancy again being not much greater than the standa errors.

In Series 3, the additional $NaHCO_3$ uses up a molecule of (equivalent to producing one of H_2O) for each molecule of NaHCO according to eg. $NaHCO_3 + I_2 + SO_2 + CH_3OH \rightarrow KI + HI + CO_2$ HSO_4CH_3.

Thus 0.39 $^0/_{00}$ $NaHCO_3$ should yield 0.08 $^0/_{00}$ more water, 0.20 $^0/_0$ of 41 $^0/_{00}$; the observed mean increase in W is 0.16 $^0/_0$, whi is in good agreement. The increase in Σ' should be 0.31 $^0/_{00}$ and t observed increase was 0.37 $^0/_{00}$. Again, these discrepancies are the same order as the standard errors of the individual observation hence agreement can be interpreted as indicating a roughly equ chance of contamination of either sample or reagent solution b ambient water.

Also, in Series I the mean value for Σ' may be compared with t value for Σ. At chlorinity 20.24 there is about 0.15 $^0/_{00}$ of HCO yielding 0.044 $^0/_{00}$ H_2O, and 0.027 $^0/_{00}$ of H_3BO_3, yielding 0.024 $^0/$ H_2O, or a total of 0.07 $^0/_{00}$ H_2O that will react with KFR. T theoretical value of 36.73 $^0/_{00}$ for Σ should therefore yield a Σ' 36.66. The observed mean value of 36.74 ± 0.14 is in good agreeme

Since organic compounds react in various fashions with KF and since little is known about the chemical nature of the orga substances in sea water, little can be said about their probab roles in the KFR determination.

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ME USES OF ANTIBIOTICS IN PHYSIOLOGICAL EXPERIMENTS IN SEA WATER[1]

By

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ABSTRACT

he oxygen content of sea water can be kept constant by use of antibiotics for ds up to more than a fortnight. With living animals present, the bacteriostatic t probably lasts for a shorter time. Chloromycetin was the most effective anti- ic used; streptomycin was also satisfactory. However, some samples of chloro- etin may prove harmful to marine animals; it sometimes inhibited the feeding pepods. A combination of chloromycetin and streptomycin proved suitable controlling bacterial action in measurements of phosphorus excretion. Since do not know the original bacterial content of the sea water used, the results bound to vary from one experiment to another, but in general the use of anti- ics can extend the scope and accuracy of physiological work.

n the open sea bacteria are generally found attached to solid ticles. Although in open sea water a large number of free bacteria not usually found, the situation changes whenever the water is ught into the laboratory, for bacteria then develop rapidly on surface of the container (Waksman and Renn, 1936; ZoBell and derson, 1936). Their multiplication may lead to considerable nges in the constituents of the water, *e. g.*, the oxygen and dis- ved phosphate.

Antibiotics have been used in sea water to control bacterial wth in experiments varying from the culture of phytoplankton anisms (Fish, 1950; Spencer, 1952) to the preservation of fish rr, *et al.*, 1950). Cviić (1953) worked on the effect of antibiotics particular species of marine bacteria. Oppenheimer (1955) found t the use of suitable antibiotics prevented bacterial growth on surface of pelagic fish eggs and he thus increased the percentage ch of both cod and sardine eggs. Walne (1958) observed increased duction of spat by *Ostrea edulis* in the presence of penicillin, and

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Contribution No. 1005 from the Woods Hole Oceanographic Institution.

Harris (1957), finding that terramycin decreased the uptake of ^{32} by *Gammarus*, concluded that it had killed the bacteria on whic *Gammarus* had fed.

In the following account the influence of a number of commo antibiotics on the respiration, feeding and excretion of marine copepods is reported. The antibiotics used are listed in Table I.

TABLE I. ANTIBIOTICS EMPLOYED

Antibiotic	*Salt*	*Strength (units)*	*Source*
Penicillin	Benzylpenicillin, crystalline potassium salt	10,000/ 50–60 mg tablet	Burroughs Wellcome, Ltd
Chloromycetin	Chloramphenicol B.P.	Pure	Parke Davis, Ltd.
Streptomycin	Dihydrostreptomycin sulphate B.P.	5 mega/g	Glaxo, Ltd.
Polymixin	Polymixin B sulphate B.P.C.	6000/mg	Burroughs Wellcome, Ltd
Tetracycline	Tetracyn hydrochloride	Pure	Pfizer, Ltd.
Bacitracin	—	70/mg	Pfizer, Ltd.

Oxygen consumption. When natural sea water is incubated in th laboratory, an initial lag period is followed first by a rapid declin and then by a more gradual decline in oxygen content (Rakestraw 1947). In measurements of the respiration of marine animals lastin for more than a few hours, allowance has to be made for this. I order to obtain sufficient reduction in oxygen content with smal animals in short-term experiments, the volume of water per individual has to be small, and this may affect metabolism. Th difficulty can be overcome by using antibiotics to keep the bacteria population low and thus increase the duration of the experiment

Sea water was filtered through a membrane filter of average por diameter < 1 μ to remove most of the living and particulate matte which might affect oxygen consumption. To these filtered samples th different antibiotics were added in concentrations of 50 mg/l. Fille bottles were kept in the dark at 10° C, and at intervals the wate was analysed for oxygen by the Winkler method. Controls withou antibiotics were also used. Results are shown in Fig. 1.

Chloromycetin was the most effective antibiotic since, wit 50 mg/l, the oxygen remained constant for 11 to 21 days; at a lowe

ncentration of 10 mg/l it was reliable for periods of only 5 to 7
ys. Streptomycin was tested several times; it maintained a con-
nt oxygen in the water for 3 to 7 days. Tetracycline was tested

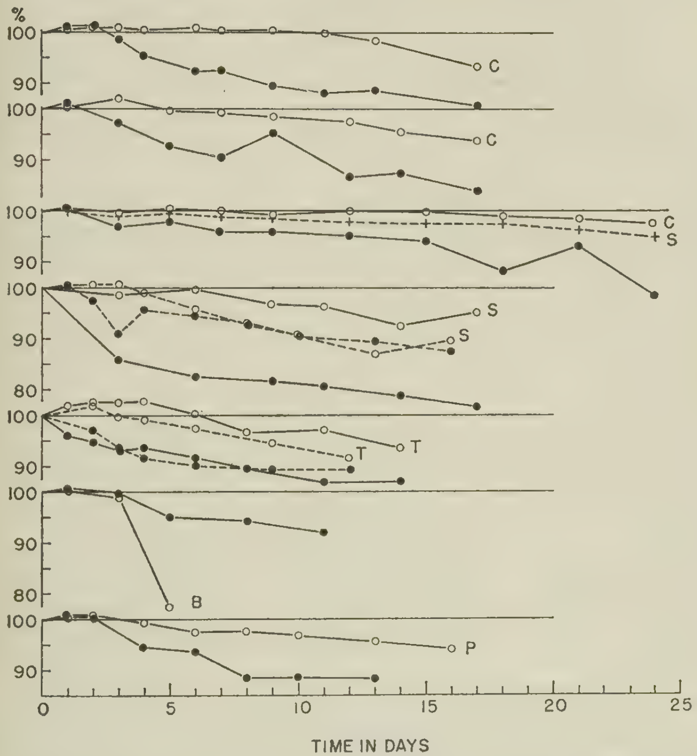

Figure 1. Oxygen consumption in samples of sea water with and without antibiotics
ded. Oxygen expressed in percent of initial value. Open circles, with antibiotic; solid
cles, without antibiotic (controls). C, Chloromycetin; S, Streptomycin; T, Tetracycline;
Bacitracin; P, Polymixin. All 50 mg/l except C in the second graph from the top,
ich had 10 mg/l.

vice; in one case there was actually a slight increase in oxygen and
e antibiotic effect lasted for 6 days; in the second, it lasted 3 to
days. A tetracycline solution turns pink on exposure to light. With
citracin there was a steep fall in oxygen after three days, this
ing more marked than in the control. Unfortunately, penicillin
nnot be used since it reacts with iodine liberated in the Winkler
ethod.

To test whether or not antibiotics affected the respiration of e
perimental animals, the oxygen consumption of two sets of fem
Calanus finmarchicus was compared, one without addition of an
biotics and one with chloromycetin and streptomycin added (50 m
of each). Each set consisted of ten bottles, each containing 5 *Calan*
there were three controls with no *Calanus*. The respiration in th
bottles with antibiotics was 0.383 μl/*Calanus*/h (range 0.29–0.
and in those without, 0.341 (range 0.17–0.46). There is therefore
significant effect.

Feeding. Although antibiotics are helpful in controlling bacter
growth when culturing marine animals, some antibiotics may i
hibit feeding or have other harmful effects. According to Dr. R.
Millar (personal communication), chloromycetin may kill oyst
larvae. Experiments on feeding were made with *Calanus* as t
animal.

One *Calanus* was put into each of a number of small dishes wh
usually contained 15 ml sea water to which the antibiotic (50 mg
and diatoms had been added. There were usually 10 experiment
Calanus and 20 controls. After about 24 hours the copepods we
removed and the amount of food eaten was measured by counti
the number of faecal pellets produced. In different experiments t
number varied with the concentration of diatoms and with t
species used. There is great individual variation, and in any exp
iment there were usually one or two *Calanus* which did not fe
at all.

With penicillin, feeding was always good. Chloromycetin usual
depressed feeding markedly as did the mixture of chloromycet
and streptomycin. Streptomycin by itself had little or no effe
The other antibiotics tested were only slightly depressing. It
interesting that the streptomycin and chloromycetin mixture us
at Millport had much less of a tendency to depress feeding th
that used at Woods Hole, which presumably came from a differe
source.

Chloromycetin proved so useful in experiments on oxygen contr
that further feeding experiments were performed with the conce
tration reduced from 50 to 25 and 10 mg/l. In the first experime
the *Calanus* fed unexpectedly well at all strengths, but in the seco
there was a rise in faecal pellet production with decreasing streng
of antibiotic.

Experiments were also carried out to find if solutions of chloro- cetin lose their harmful effect on keeping. As before, the cope- is did not feed well, but there was no apparent change in feeding solutions one day and nine days old.

Excretion. In a series of experiments on phosphorus excretion by ine copepods, cultures of diatoms and flagellates labelled with were used as food. An attempt was then made to estimate the ction by measuring either the decrease in ^{32}P in the copepod lf or the gain in ^{32}P by the water in which the copepod had n kept. The first method is less suitable since it is less accurate involves the exposure of the copepod in a small drop of water several minutes, which may injure it. The figures of loss from copepod and gain by the water should have been the same, but only one set of experiments did they agree fairly well, for about days. In most cases the loss from the copepod was much above gain by the water.

Since it is probable that bacteria on the walls of the container ke up phosphorus, two series of experiments were carried out th antibiotics (chloromycetin and streptomycin, 50 mg/l of each) led to the water. In these the measurements of loss from the dy and gain by the water were much closer. In the first experiment, th six individuals, measurements were made on alternate days, d the ratio of gain of P in the water to loss from the copepod body ried from 85 to 112 $^{0}/_{0}$, averaging 96.4 $^{0}/_{0}$. In the second (14 dividuals), the interval between measurements was increased to ree days, and in this case the ratio varied from 80 to 111 $^{0}/_{0}$, with average of 99 $^{0}/_{0}$. The antibiotics therefore make it possible to a fairly accurate estimate of phosphorus excretion without any rm to the animal. Penicillin or a combination of penicillin and eptomycin would probably be more suitable since neither affects ding.

We should like to thank the Director and Staff of the Woods le Oceanographic Institution for their hospitality. We are also teful to Dr. R. Cruickshank, Professor of Bacteriology, University Edinburgh, for his help and to Messrs. Burroughs Wellcome & Co. d Messrs. Pfizer, Ltd. for samples of antibiotics.

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C. WYVILLE THOMSON'S LETTERS TO STAFF-COMMANDER THOMAS H. TIZARD, 1877–1881

BY

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ABSTRACT

ese original letters from Thomson to Tizard are concerned with the publica- of the results of the CHALLENGER Expedition, as well as the study of the Faroe nel and the eventual delineation of the Wyville Thomson Ridge with its rsity of "cold and warm area" bottom fauna. They also provide evidence of Thom- indefatigability as well as certain historical sidelights.

INTRODUCTION

uite by chance, Sir Henry Tizard, whom we had never met, nt the night of 6 November 1951 in the Fellows' guest suite of venport College, Yale University. At breakfast in the Master's use the next morning we talked about the history of oceano- phy in the second half of the 19th century—in detail about the yage of H.M.S. CHALLENGER, Sir Charles Wyville Thomson, Sir n Murray, and other pertinent matters which had interested us an avocation over the past three or four years. After some time Henry queried, "Does my name mean anything to you?" We lied that the only other Tizard we knew about was the one of ALLENGER, KNIGHT ERRANT, and TRITON fame in oceanographic rk of the 1870's and early 1880's. "My father," announced Sir nry.

He then stated that he was quite sure he had some original letters m Wyville Thomson to his father. It was disappointing to learn ne months later that he had not been able to find them. On September 1957 we were Sir Henry's guests for lunch at *The enæum*. Three weeks later he wrote, "Another hunt has brought light about 50 letters from Wyville Thomson to my father. They d been put away many years ago so carefully and methodically t I couldn't find them for a long time!" Most graciously, and with prehension, he sent 52 such letters across the Atlantic. Nineteen of them, the most interesting, form the basis of this article. Writ about Thomson's long-hand letters, Sir Henry noted, "I shud to think of the trouble you will have in deciphering them!" indicated in earlier writings on this subject (1), Sir Wyville's h is most unhappy. We herewith acknowledge our great gratitude Sir Henry Tizard and his family[1].

THE BACKGROUND

Her Majesty's ship Challenger returned to England on 24 M 1876 from the last leg of her three-and-a-half year voyage arou the world (2). In the course of traversing a track of 68,930 m she had occupied 362 oceanographic stations. As Huxley poin out at a dinner in honor of the Challenger staff in Edinburgh 7 July 1876, ". . . the peculiarity of the *Challenger* Expedition that in her case the cruise became secondary and the scient object primary; that she was, in fact, fitted up and instructed w the view of obtaining certain scientific data which were requi for the further progress of natural knowledge. In her case the d of geographical exploration was reduced to *nil*, and the duty scientific investigation had become paramount" (3).

In the summer of 1876 Sir Charles Wyville Thomson, who h been Director of the Civilian Scientific Staff of the Challeng during her entire voyage, was instructed by Her Majesty's Gove ment "to prepare a detailed Report on the scientific results of expedition" (4). Actually Thomson is at some pains to show t he never would have undertaken the scientific direction in the fi without an understanding that he would have charge of "the wo ing out of the results in the department under my directio on this subject as well as on the planning for the disposition specimens, estimated costs, *etc.*, there was considerable correspo ence between Thomson and the Admiralty[2] in 1874 and 1 while the Challenger was in midvoyage (5). Subsequently, September 1876, arrangements for publication and "disposal collections" were transferred from the Admiralty to the Treasu and the Challenger Expedition Commission under Thomso direction was established in Edinburgh. It was mainly the work getting under way the *Challenger Report* (which resulted in the ge royal quarto volumes [6] that form the main outlines of modern anography) as well as the resumption of his duties as Regius fessor of Natural History at the University of Edinburgh that upied Thomson for the next five years; in the latter part of 1881 was forced to resign his educational duties because of ill health (7). died on 10 March 1882 in Linlithgow, where he had been born years before, almost to the day.

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[1] 23 August 1855 – 8 October 1959.

[2] Specifically with the Hydrographer, Capt. Frederick Evans, and with Secretary, Admiral Robert Hall.

he Navy List for April 1873 (8) shows that Thomas Henry rd was Navigating Lieutenant aboard the CHALLENGER during oceanographic voyage, but in the Report he is consistently re- ed to as Staff-Commander. There is abundant testimony as to skill as navigator, surveyor, and scientific observer, as well as the respect in which he was held by all hands—see, for example, irc (9), Spry (10), and the Admiralty Digests in the Public Rec- Office in London. Under Captain George S. Nares (1872–'74) then under Captain Frank T. Thomson (1875–'76), he had rge of the hydrographic, magnetic (with Commander J. F. L. P. clear), and meteorological work; indeed, he contributed major tions to the *Challenger Report* (11) (12). He was later Captain of KNIGHT ERRANT (1880) and TRITON (1882) on expeditions to Faroe Channel with Sir John Murray[3] to survey and study the ttom fauna on the two sides of the Wyville Thomson Ridge (see low). Captain Tizard and Sir Wyville became close friends; the ters here printed contain more intimacies than most we have seen.

THE LETTERS

This correspondence deals chiefly with two matters: the prepa- tion and publication of the early CHALLENGER volumes and the ploration of the Faroe Channel. It is, to the best of our ability, ranged in chronological order.

Bonsyde
Linlithgow, N.B.
July 16th

My dear Tizard,

I should have written you long ago to thank you for your kindly sending me the article from the Standard, which was certainly more pleasant than some other newspaper articles have been lately. I have been waiting however from day to day for instructions from the Treasury & the Stationery Office, & they have come in some shape at last. I scarcely know whether they are satisfactory or not. In the first place the Treasury say that printing & all engraving, and all such work must come through the Stati ery Office, and if that order is pushed to the extreme it will put off enormous amount of time. In the second place they inform me that costs for printing, engraving, paper etc., etc., of that kind are not incluc in my grant of £ 4000 a year, which is meant purely for the Scientific wo That is a great relief.

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[3] Young naturalist on the CHALLENGER, and successor to Wyville Thomson in direction of the work of the CHALLENGER Office in Edinburgh, which he com- ted in 1895.

My next move must be to get a full explanation from the Station Office. I am given to understand however that they will sanction and any reasonable & economical way of doing what is evidently necessa

There is a rule at the Stationery Office that the whole mss: of any volu must be sent in before it is printed. I wrote that I thought there wo be no difficulty about that if they chose to pay the printing—and if tl printed Vol 2 before Vol 1. We shall however evidently require to send the whole mss of Vol 2 at once, and they do not want it until the new c tract in Scotland begins—that is till about October or November.

Will you, before you go off, let me know in a form which I can put the Stationery Office how many plates & charts will be needed for the fi two Vols and how you propose getting them done and what would be probable expense.

I have not yet gone over fully the charts. It seems to me that they all right. I will send them back to you in a day or two.

The instruments arrived this morning. Tait has gone over to St Andr but he will be back in a few days to a meeting of Science Faculty and will then tackle the question. The instruments are all right I should thi but I have not unpacked them.

What we have to do then seems to me to put the 2d Vol complet into form in the first place, and to ask instructions from the Station Office what is to be done with it—to send in to the Stationery Offic detailed statement of the number of Charts & plates we require for first two Vols and the way we propose to get them done and the proba expense. If you will give me material for this latter I will see it carr through—Charts—and temperature sections—and any plates of cur which may be useful in generalizing any of the observations magne or meteorological.

I shall not be in London unless there is some special reason for it u the last week of August at soonest. I shall be abroad in the first half September & after that at work either in London or here. So it will s capitally for you to take your outing now.

Towards the end of September if the second Vol is ready you mi run down here perhaps & we could set the printers to work & settle ab type & form.

Lady Thomson & Miss Dawson send their kind remembrances. M Dawson says she has a debt to pay you, which she incurred on the Hope Hunt, when you come back. I saw Jock Murray in great form today. is expecting Campbell down & they are coming out to us for a day.

Yours vyty

C. Wyville Thomson

The reference to the Treasury helps to fix the year of this letter
877 (p. 348). Sir Wyville may have "been waiting from day to
for instructions", but he was certainly keeping himself occu-
i[4]. Moreover, he had indicated in a letter from Valparaiso as long
ore as 22 November 1875 that it would take a full year with
after landing to get" . . . the collections roughly arranged and
into a condition for distribution to experts, on the 1st May
7, but not before that date" (5).

he reference to his grant of £ 4000 a year also harks back to
letter from Valparaiso (xi.22.'75) in which he states, "I do not
k that the account of the voyage could be fully published and
whole matter closed in less than five years[5] from the 1st of May
7. During these five years the expenses might be estimated at
000 a year, one year with another, supposing the printing to be
e at the Government printing-office" (5).

n the third paragraph of the letter dated 16 July, Thomson re-
to ". . . printing Vol 2 before Vol 1." These volumes form the nar-
ive of the voyage; the second, consisting of the Magnetical and
teorological Results (12), appeared in 1882, while the first, dealing
h the Narrative and General Account of the Scientific Results
the Expedition (11), did not appear until 1885. Actually the first
ALLENGER volume that appeared was in the Zoology series in
80 (4); it was succeeded by five others in the years 1881 and 1882.

The instruments in the sixth paragraph are the CHALLENGER
rmometers; P. G. Tait, Professor of Natural Philosophy at
inburgh, worked on the possible error introduced by the effect
pressure in the deep-sea temperature readings taken on the ex-
lition (20) (see letter of 4 December 1877 and accompanying
notation).

Later Thomson speaks of going abroad in September—the oc-

In September 1876 at Glasgow Thomson "shared 'lionship' . . . (his) address on
Results o (*sic*) the *CHALLENGER* Expedition was very successful" (13). He
ured at the Birmingham and Midland Institute on 12 March 1877 (14); also in
sgow on 23 November 1876 "On the Conditions of the Antarctic" (15). He re-
ed a Royal (Society) Medal on 30 November (16), and on the same day he was
de a member of the Council of the Royal Society of Edinburgh (17). He gave
Rede Lecture in the Senate-house at Cambridge on 25 May (18), and in the
iversity of Edinburgh "session 1876–1877 (his) lectures were attended by up-
ds of 400 students" (19).

It took $17^1/_2$ years.

casion when he went to the tercentenary of Uppsala as a represe
ative of the University of Edinburgh, and when he was crea
a Knight of the Royal Order of the Polar Star by the King
Sweden (21) (22). Earlier in the summer he had received the deg
of Doctor of Philosophy, *Honoris causa*, at the University of Jena (
The original diploma[6], at the Department of Zoology, The Ashwo
Laboratory, University of Edinburgh, appears to be signed on
right margin by Ernst Haeckel[7] and bears, in long-hand unc
neath, the date 27 July 1877. It seems that Thomson took
degree *in absentia*.

In the final paragraph Sir Wyville speaks of Lady Thomson
Miss Dawson. Lady Thomson's younger sister was Frances,
doubtedly the Miss Dawson referred to above. Jock Murray is
course Sir John Murray. Campbell is Sub-Lieutenant Lord Geo
Campbell, son of the Duke of Argyll, author of a popular bo
"Log Letters from the *Challenger*"—not originally written for p
lication, but for which purpose he rounded "off only the most
breaking angularities" (25).

Bonsyde
Linlithgow
August 17th

My dear Tizard,

I hope you had better weather for your holiday than we have been gett
here. We have had one fine day during the last six weeks. At least I
told there was one, for I happened to be in London at the time.

I ran up for a few hours and saw the Treasury and Stationery O
people and had a long talk with them, and on my return I wrote a let
to which I got the inclosed reply. Please read it & note its contents & s
it back to me.

There is no objection to our following the plan we propose. I wo
rather not suggest that part of the printing be done in London. It se
to me better to keep it all together in one job with the same types &
same style, and we can easily send the Tables by post for correction. Th
is no objection to the second vol being commenced within a couple
months. Neill & Co are enlarging their premises & would rather not be
for a little.

---

[6] The gift of Mrs. Andrew A. N. Buchanan, niece of Frank Thomson, Sir Wyvi
and Lady Thomson's only child.

[7] The author of four contributions to the *Challenger Report*; among these
Radiolaria (24) is perhaps the most famous of the CHALLENGER volumes—two p
text (2155 pp.), one part plates (140 and one map). Haeckel was clearly respons
for Thomson's honorary degree at Jena.

The engraving will be put as you see into Mr. Maltby's (*sic*) hands. rhaps you would see him & find out what he thinks of stone versus pper. Let us have the clearest and best method. . . .

Could you, do you think, during the next fortnight or so get some notion the order of the second volume, & get the first part of it into sufficient ape to have a sample sheet printed. I am going off for a run on Friday t. To Upsala and perhaps on to Munich. I have to make some arrangents about the the (*sic*) Crustacea etc. with one or two people. I cannot pend upon being back much within a month. I send you back the arts & diagram.

Yours vy ty
C. Wyville Thomson.

his letter was also written in 1877, since he refers to Uppsala e last paragraph (see above). In the third paragraph mention ade of Neill & Co., an Edinburgh printing firm which apparently the contract; the CHALLENGER volumes all read PRINTED FOR MAJESTY'S STATIONERY OFFICE on one page and PRINTED BY L AND COMPANY, EDINBURGH on the next. Later, comment is le about engraving and "Mr. Maltby", which Thomson often spelled for Malby; examination of early and late volumes of the *llenger Report* shows that the charts and diagrams were engraved Malby & Sons on copper. There is a note, presumably Tizard's, the back of this letter which says: "Suggested to Sir W. T. some plates should be engraved on copper & some on stone ppears to be most suitable in consultation with Mr. Malby."

University
Edinburgh
Nov. 12th

y dear Tizard,

Many thanks—I will send back the plans in a few days, but it will take while to go over the letter-press & beside I suppose I should do so with view of combining all I have to say.

The printers are going on with the 2d vol but it takes a lot of correcting fore they get into the way of setting up the tables.

I have heard nothing more from your friend the photographer and he s a lot of the most valuable of the Challenger negatives. I must try & get em back somehow through the Stereoscopic Co. or otherwise. The last ing I heard of Thorpe was getting my own set utterly bedevilled & being ld that proofs of the others would be sent immediately. I hope nothing s befallen the plates.

I have been thinking over the beginning of the first chapter but I have t had time yet to get it into shape. I have to correspond with about

forty people as to the details of the Nat Hist work and also with the Station
Office & the Treasury. Through the marvellous arragmts of the latter t
I have usually to write to the rest that I have "no authority" to autho
them to do anything! So I do not exactly see how I am to get on.

With kind regards in which my wife & Miss D. join.

Believe me
Yrs vy tly
C. Wyville Thomson

P.S. Tell me when next you write what appntmt Nares has got & w
he leaves. I had a note from him some little time ago but he said not
about it.

From its contents, this letter was almost certainly written
1877. The *Challenger Report* was still in its initial stage, and a le
dated 15 February (no doubt in 1878, see below) contains furt
acid comments on the CHALLENGER negatives.

The art of photography was still in its early days in this peri
the first successful daguerreotype having been taken only 40 ye
before Thomson wrote this letter (26); but the Narrative conta
35 photographic reproductions. The original CHALLENGER negati
—some 456 in number—are still preserved in the John Murray Ro
at the British Museum of Natural History.

The postscript refers to Sir George S. Nares, K.C.B., F.R
". . . under whose direction the whole system of observation
carried out during the first two years of the voyage" (27; also
above).

Dec. 4th.

My dear Tizard,

I like the sketch charts very much. They will of course look better w
they are more filled up. The account of Kerguelen Island & the Sc
also seems all that can be desired from your point of view. I have not
time yet to consider fully how your notes are to be incorporated with
other matters. I do not see any great difficulty however. I have
going carefully over the Southern work again and writing my not
about the Southern ice—like you. I wonder if we shall agree.

I suppose you saw the lecture I gave last winter in Glasgow on it
'Nature'.

Some more experiments have been made on the Thermometers
although we have not . . . to the bottom of the business, one thing is cer
that we had no right to apply the correction we did. Some error may c
in through pressure of the portion of the tube below the bulb & above
mercury but such error must be very slight. We are making preparation
experiments on a large scale to test this and I hope to be able to give

ome results ere long. Now the question is what we are to do about the Temper- ture Tables. There seems no doubt that the former corrections must be ancelled however much trouble this may take. The only doubt is whether e should wait to see whether they should be replaced by another correction another principle. I think myself that this is unnecessary. The correction there be one must be infinitesimal—quite within the limits of error of bservation. It might be mentioned that there is such a slight correction ut I think it would be nonsense to put it in throughout and that the ressure error should be left out & the calibration error only needed. I ppose this will give an awful amount of bother but the only plan seems be to tackle it at once. I am still in difficulty with the Stationery Office bout the plates & printing etc., etc. but I have some hopes of being allowed go on smoothly in the course of a week.

Believe me
Yrs vyty
C. Wyville Thomson

This letter was written in 1877; the lecture he gave in Glasgow s on 23 November 1876 (15).

Tait's writings on the pressure errors of the CHALLENGER thermom- ers are extensive (28, 29, 30, 31, and 20). Thomson had been told Captain J. E. Davis of the Admiralty to apply a correction of least half a degree F. heating for every mile of depth. Tait wrote 0):

> Half-a-degree Fahrenheit per mile of depth may seem to be a matter of very little consequence; but when we recollect that some of the Challenger soundings were made at depths nearly approaching six miles, we find that we have sometimes to deal with a correction of 3° F., enough to modify seriously our theories of ocean circulation. For it can never be too strongly impressed on the student of science that there is no such thing as greatness or smallness in itself; what is very small relatively to one class of quantities may be very great relatively to another and different one. All the temperature differences, except near the surface of the sea, though important in their consequences, are very small relatively to differences of temperature in the atmosphere; but, just because they are so small, small errors in the determination of their values are important:—thus it was imperative to decide whether the corrections assigned by Captain Davis are necessary.

Tait concluded after much experimentation that "if the Challenger ermometers had had no aneurisms, the amount of correction . would have been somewhat less than 0.05° F. . . . for every mile of pth. All the [Challenger] thermometers which have large aneurisms ve had special calculations made for them, but in no case does

the correction to be applied to the minimum index exceed 0.1
or about $\frac{1}{7}$th of a degree per mile of depth." Sir Wyville's co
ment that "The correction if there be one must be infinitesima
seems to have been reasonably accurate. Murray (32, Part I
Introduction) wrote: "These temperatures were plotted on t
squares, as represented on each Plate, by Staff-Commander Tizar
R.N., simply as observed and corrected for instrumental errors
No correction for pressure appears to have been included in t
Challenger Reports.

Edin. Jan 19th

My dear Tizard,

I send you Buchanan's 'Laboratory Book' with all the Specific Gravit
corrected. I do not know what you intend by the 'Results he sent to t
Royal Society'. If you mean the gas determinations I have not got the
The only thing I have is a short notice in one of the late numbers of Natu
(some months ago now).

Yours vy ty
C. Wyville Thomson

This letter was written in 1878. J. Y. Buchanan, chemist a
physicist on the CHALLENGER (11), published a short article
Nature (33), 26 July 1877, which discusses the amount of oxyg
at different depths. Thomson, at the writing of this letter, had a
parently not seen *Nature* (34) for 27 December 1877, in whi
Buchanan crossed swords with Sir Wyville and defended his positi
"that between 200 and 400 fathoms there is a great consumpti
of oxygen going on, and, as it is difficult to conceive its being co
sumed otherwise than by living creatures, the conclusion is forc
on us that animal life must be particularly abundant and acti
at this depth."

Bonsyde
Linlithgow, N.B.
Feby 15th

My dear Tizard,

I have not yet got any intimation of your departure for the Golden Ho
so I suppose you are still all right.

We here have no faith in war. We are just as sure that the cloud w
blow over as we are sure of anything, but that may be overconfiden

There are two little matters I want to ask you about. 1st. Do you reme
ber on what data you gave me the approximation in my book to the equiv
lents of velocity & pressure of the wind? I forget. You remember you ga
me the material for a scale, and I have been asked where it came fro
Can you recall the circumstances? 2d. About Mr. Thorpe—about a ye

I sent him a box of Challenger negatives. Most unluckily some of value they were from the Admiralty Islands. I at the same time sent him a to mount for me which he botched. I have written to him twice about m once & last a fortnight ago asking him to return the negatives, if has done nothing with them but there has been no answer. What shall io? I have no doubt that the Stereoscopic Co. will say that they are not ponsible, and I fear the photos are lost. It is very provoking. Do you r see the man? Or has he gone into forced retreat somewhere?

The printing is getting on woefully slowly. I hope there is some little nce of a spurt shortly.

Ever trly ys
C. Wyville Thomson

his letter was also written in 1878. The Golden Horn, an inlet he Bosporus, as used here is synonymous with Constantinople Istanbul). Turkish resistance to the Russians had failed fast ecember 1877; British interests now became sufficiently involved hat Parliament was summoned before the usual time, on 17 uary 1878. The fleet was then ordered into the Sea of Marmora (35).

Bonsyde
Linlithgow, N.B.
March 3$^{\underline{d}}$

y dear Tizard,

I should have answered your note sooner but had to think the matter er. Certainly the map should not be over crowded and I think the points require most are

depth, may I think be done by tints, and contour lines, so we are relieved of that.

Nature of the bottom must go in for every station.

Number of station, must go in.

Surface-water movement (surface current) ought to go in as far as possible.

Temperatures. The surface temperature should be given when there is room I think, and here & there where the stations are close, and the bottom temperature in like manner, with some distinguishing kind of type or bracket. I think that is about all we can have except the line of drift ice & a dotted line for the extent of gulf weed.

About the bottom temperatures. In the tables you have prepared you op at 1500 fathoms. There are several points about the tables & temperares which I think we had better talk over. Can you arrange to run down re for a week or two—say about the first week of April? We hope to have mething like spring weather then and I hope to be strong enough for a asonable amount of work . . .

Yrs vy ty
C. Wyville Thomson

This letter was quite certainly written in 1878; in content it well with the preceding and succeeding letters whose dates are initely established. The invitation from Thomson to Tizard visit him in Scotland is only one of a number that have come our attention. Thomson's hoping "to be strong enough for a reas able amount of work" would seem to indicate that Sir Wy had been sick—one of the earlier of a series of recurring bout illness which were to plague him for the balance of his life.

April 29th
1878

My dear Tizard,

I hope you get the Mss all right. The magnetic work is taking an enorm amount of time. If we get on no faster than we are going now I do see when we can expect to be finished. The delay is partly with the prin and chiefly at the Hydrographic Office. We are not half through y think it might be well for you in case of accidents to send me the Meteoro ical work with titles, etc. all ready for the printer and at the same tim send me some notes as to how & where you wish to arrange the accoun the instruments, methods etc. In fact you might send a rough 'content the 1st & 2d Volumes according to your notion & we can see whether question arises.

It is certainly safer to put in the temperatures uncorrected. Have gone into the question of the history of Thermometers? I have h nothing further about Maltby's (*sic*) account. It will be all right howe I do not expect any strain on the finances this year. I earnestly hope there may be no "service to the East", but things do not seem to be loo better.

My wife & Miss Dawson unite with me in kind regards.

Believe me
Yours vy tly
C. Wyville Thomson

This is one of the few letters in this correspondence which is f dated. The "service to the East" is of course a further referenc the crisis that led to the Congress of Berlin (see letter of 15 Febru 1878).

Bonsyde
Linlithgow, N.B
Sunday

My dear Tizard,

I think it would be far better for all the difference in price to do sections on copper . . . .

I have not had time yet even to look at the Temperature Chapt the account of the thermometers. I will do so however as soon as I ca t you know what I think of the line you have taken. I have very decided pinions myself on the subject. I think the Instrument makers deserve ery little credit. The ideas are not theirs and the instruments are as a rule ery carelessly made! I will go carefully over these weather charts & see hich will answer my purpose best, and then we can see about the cor-ctions. There are only three or four I think which will be needed.

I am very sorry that you have not got the arrangement made at the dmiralty which you wished. At all events I hope you will not go off efore the 1st Vol is put into shape.

I have like a fool arranged to give the address to the Geographical ction this year and it is hanging round my neck like a millstone. With nd regards

Yours vy ty
C. Wyville Thomson

This letter was certainly written in 1878, probably in June or y. The 27 June 1878 issue of *Nature* (36) announced that at the rty-eighth Annual Meeting of the British Association, which was d in Dublin in August of that year, Thomson would be President the Geography section. And the 22 August issue (37) carried in l the address which had been hanging round his neck like a mill-ne. Sir Wyville frequently complained to his intimates about e preparation of lectures; it is apparent that he was at great ins to have them as perfect as possible.

During these same meetings the honorary degree of LL.D. was nferred on Thomson at Trinity College (38). Dr. Webb, Regius ofessor of Laws, presented him with the following citation (39):

> *Praesento vobis Wyville C. T. Thomson,*
> *equitem auratum, Neptuni Provocatorem.*
> *Hic et Nereidum domos invasit, et ab*
> *ipso Proteo arcana extorsit.*[8]

Edin
Sept 24th
1878

My dear Tizard,

I have been off duty & in the country for a short time—not very well—only a bit knocked up & now nearly all right again.

I am very sorry there is a chance of your leaving. I consider however that we are most fortunate in your having been with us so long. If you have to go I must simply combine your Hydrographic work with the rest of the general account as best I can. There was a little difficulty in fitting in the introductory notes about the Meteorology. I think it is all ri now and you will probably get a proof tomorrow. In the mean time th are making progress with the Tables to the best of the power of the print which does not seem to be great.

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[8] "Knight, Challenger of Neptune. This man invaded the very home of the reids, and wrested from Proteus himself his secrets."

We are getting on however. A lot of information is coming in with reg to the fauna & to Chemical affairs . . . . .

You saw I daresay the notice I gave of our progress at the Brit: As

I am not sure that our printing in Edinburgh was very wise. As it I do not see how we can go on faster.

Believe me
Yrs vy try
C. Wyville Thomson

This fully dated letter and letters to follow continue to refer his ill health. Tizard's leaving the Hydrographic Office for oth duty is obviously a matter of deep concern to Thomson. The ne to last paragraph must refer to an article in *Nature* for 12 Se tember 1878, which says: "Some causes of delay have occurre and there has been the regulation amount of friction insepara from the working of a complicated piece of machinery, but my feeli is that on the whole things are going on wonderfully well" (40).

Bonsyde
Linlithgow, N.B.
Sunday

My dear Tizard,

I need scarcely say that this severe illness putting a stop to all my wo was a great shock to me & a source of great vexation.

I had not been quite right for some time. I doubt if I was careful enou in hot places. You may perhaps remember that at Cape York I had son thing like a slight sun stroke which laid me up for a day or two. I ha never felt quite comfortable about the nape of the neck since. This m be the last of it. I am much better though the doctors still prescribe absol rest. They say however that shortly I may commence again gently.

I scarcely remember precisely which of the illustrations you propos to use. Many of Wilds sketches of animals will do for the naturalists b I fear the diagrams of temperatures etc. etc. will not do, and besides th are virtually repeated in the plans. I think you had better write & t me your notion in brief. I have the wood-blocks absolutely at my dispos so you can have what you require. The figures of the dredge & trawl the water-bottles & other bits of apparatus will no doubt answer. Th were carefully done.

I will see that you get a copy of the short book at all events.

I suppose I shall have to go abroad somewhere. The Nile I fear is too ot, but I must wait a little yet before doing anything. With best regards om all of us

Yrs very truly
C. Wyville Thomson

his letter was written in 1879, probably in either July or August. dman (7: 55, 56) says that Thomson had an attack of paralysis une 1879. As vice president of the Royal Society of Edinburgh, nson was in the chair on 2 June (41). But the 19 June issue of *re* (42) states that he "was last week compelled, from sudden position, to relinquish his course of lectures at the University Edinburgh. . . . His large class of between 400 to 500 students accordingly been entrusted to Prof. Alleyne Nicholson, of St. trews." A week later the same journal (43) reported, "It will ome time before he can attend to business letters. In the mean- e all communications connected with *Challenger* matters should addressed either to Mr. John Murray or his Secretary."

he "copy of the short book" may refer to Volume I (Zoology) the *Challenger Reports* (4), published in 1880—the first of the ire lot to appear.

Nov. 28th 1879.
Bonsyde

y dear Tizard,

I think you rather misunderstood my question. I was perfectly aware hat your work about the Specific Gravities had been arranged & was nportant but I had forgotten what it was precisely—and when I happened notice the sp. g. columns in the 1st Table I got puzzled a little.

The form of these tables is I think excellent. I will have the additional heets printed off. Since we have this material I have no doubt it ought be published, but I confess I have a great doubt of the value of the reater part of it. I am glad to hear you say that you think the surface : gs: of so much value. I have spoken to several men who ought to know, nd they thought them of no value whatever, depending on local accidents, hiefly weather (sun and rain) entirely, that is except in such cases as e South with the melting ice. If you have time I wish you would tell e a little in detail on what your conviction rests.

If we had no analyses of the waters the bottom and intermediate sp: s would be of great value, and they are of some importance as it is.

Some of the deepest might be corrected for pressure. It would be interesting to know what the density of the water in which the deepest fishes live, eally is.

It is fortunate that Buchanan has already written what I think is ample bout the Hydrometers, for after some representation he made to the

Treasury, they sent me very sharp orders that he was not to be employ again. No use talking about this. I do not think he is up to much but would have been very convenient if it had been possible to get him to fin up some things which no one who was not with us can do so well.

I wish I could get rightly at the first Volume. Of course my illness p me off a bit, but the main thing is the time it takes to get in the lists the animals from the stations. I hope to have it well in hand however af Xmas, & to be a little stronger.

I think St Pauls Rocks look well. I shall have about 30 such plat I will get you to come down if you can spare the time as soon as I see way to go to press.

If the sp: gs: are correct what is the conceivable use of the colum about the immersion of the Hydrometers?

With kind regards.

Yrs vy truly
C. Wyville Thomson

P.S. I enclose one of the lists I got Wild to make out for me from Buchana books. I have the whole in this form. Those from the Atlantic are in my bo

Thomson's health was improved by late 1879; the 13 Novemb issue of *Nature* (44) reports, "We are pleased to hear that Pr Sir Wyville Thomson is now much better, and able to conduct t correspondence in connection with the *Challenger* work."

It appears that Tizard stayed on at the Hydrographic Off working on CHALLENGER material pretty well through 1879.

Buchanan, chemist and physicist of the CHALLENGER Expediti was author of the resultant work on the specific gravity of samp of ocean water (45). Subsequently he became associated with t Prince of Monaco in the latter's extensive oceanographic expl ations over the turn into the twentieth century.

In the post-script "my book" refers to Thomson's two volum concerning the voyage of the CHALLENGER in the Atlantic (8); t matching work for the Pacific was never published.

Bonsyde
Linlithgow, N.B.
Dec. 19th

My dear Tizard,

I very heartily congratulate you on having got a berth which suits y so well. I am getting steadily better and I hope ere long to feel sure enou of myself to write to the Hydrographer about finishing up that very n Hebridean point next summer. It should give us a nice pocket test for those temperature questions.

I am not convinced yet that those extremely critical (?) determinations surface sp. G. are other than a loss of time. They must be published wever since we have them. I only roughly tested the thing once between nte Video & Tristan. We ran that section in 18 days—9 fine & 9 wet. mean of the surface Sp. G. on the wet days was something like 1.025–91 d on the dry 1.026–39. Now this being the case what can be the value extreme accuracy & a figure in the fifth decimal place I fail to see! I your reasons for putting in these columns. They may be of some use connection with the behaviour of glass.

You have not sent me a blank sheet of the Table paper. If you have one u might send it.

I hope to see you here long before you have to go to sea. We all join best regards and wish you a happy Xmas.

Yrs ever ty
C. Wyville Thomson

S. Will you give my kindest remembrances & best wishes of the season the Hydrographer. Tell him that I mean to write to him very shortly t that it does not come *quite* easy to me yet.

eferences to Thomson's health, to Tizard's sea duty, and to Hebridean point, date this letter in 1879.

his and the remaining letters, except the last, deal with the loration of the Faroe Channel by Thomson, Tizard and John ray. In the course of the LIGHTNING and PORCUPINE Expeditions er the direction of W. B. Carpenter, Gwyn Jeffries and Thom- in 1868 and 1869, contiguous areas having widely different perature conditions were discovered in the deeper water be- en the northwest tip of Scotland (Cape Wrath) and the Faroe nds (46). In 1869 Carpenter described this phenomenon as fol- s, "two very different Submarine Climates exist in the deep nnel; a *minimum* temperature of 32° being registered in some s of this channel, whilst in other parts of it, *at the same depths, with the same surface-temperature* (never varying much from 52°) *minimum* temperature registered was never lower than 46°, showing a difference of at least 14°" (47). In discussing this liar situation in 1872, Thomson wrote,

> he cold water abuts against the warm—there is no barrier between them. hat prevents the cold water from slipping, by virtue of its greater weight, der the warm water off the Butt of the Lews?[9] It is quite evident that

---

The northern tip of the Hebrides.

> there must be some force at work keeping the warm water in that partic position, or, if it be moving, compelling it to follow that particular co (48).

Eight years later he wrote (thinking now of the problem of deep-water circulation of the great ocean basins),

> . . . during the cruise of the *Challenger*, Staff-Commander Tizard and I often in our minds the singular instance of contiguous areas of wi different temperature conditions which had been examined by Dr. penter and myself (49).

Thomson had at first thought that the Faroe Channel phenome was

> . . . an indraught of cold water, passing southwards from the Spitzber Sea, [which] was met at its mouth and banked in by the north-east extension of the Gulf Stream, forming along the line of contact and pa mixture a 'cold wall'. This view presented many difficulties, and on re sidering the matter it now seemed certain that if our generalization regard to the cause of great differences in bottom temperatures wi short distances be correct, a submarine ridge rising to within about fathoms of the surface must extend across the mouth of the channel betw the coast of Scotland and the Faroe banks.

Hence his desire for a test of the very neat Hebridean point.

Morley's
Wednesday Trafalgar Square

My dear Tizard,

I had a long talk with the Hydrographer today. He was fully up in question and was personally most anxious to do everything in his po but he said it was absolutely impossible for the present year at all ev to arrange for any other vessel, or in fact to do anything which would h to appear on paper. As the result of a long chat this scheme was prop —that you should take your Knight-Errant up to Stornoway during good weather, and sound out the supposed ridge so far as you can with resources of your ship and what assistance you can get. Murray would with you with the necessary trawling gear—for now I come to the n tragical part of my story. The doctors put an absolute veto on my g any distance to sea without a surgeon on board, so I should have to at Stornoway & take a run out when I could get a chance.

It would certainly be of great importance that we get this bit of in mation this summer and on the principle of a half loaf being better t no bread I suppose we should do what we can.

The Hydrographer suggests that you should find out about the little gines of the Challenger launch & barge & apply for what you can disver—for your own sounding exigencies. We leave for home on Saturday obably.

Yrs vy tly
C. Wyville Thomson

Bonsyde
Linlithgow, N.B.
June 3d

dear Tizard,

will be ready for you any time about the middle of July which will you best. After I have made some further inquiries I will write in form the Hydrographer.

The inquiries are in the direction of overcoming the engine difficulty. vould be very sorry to lose all chance of one or two hauls on each side the ridge, and will not for the sake of a few pounds.

I wish you would write me a line for my use in writing to the Hydrog— licating the minimum scheme for the present summer. When I was in wn the other day I pointed out to him the supposed line of the ridge, d suggested too that zigzagging across that for perhaps a fortnight of e weather from about Cape Wrath to the Faroe Banks might answer r purpose. I suppose that is not far from it.

I will write to you again when I have more definite news about the engine. suppose you have room to screw down or lash a small steam winch on e deck.

Yours vy ty
C. Wyville Thomson

hese letters and the succeeding ones, until otherwise noted, e all written in 1880. Thomson wrote *in form* to the Hydroher on 16 June, and his reference to not losing a chance of vling on either side of the ridge[10] for the sake of a few pounds xplained in his official letter of application: "As remarkable erences in the distribution of marine animals accompany these erences in temperature, I should greatly regret if we had not w casts of the trawl on each side of the line, but any additional ense involved for this purpose I will gladly meet" (49). The ers that follow show Thomson's determination to get samples he bottom fauna from the contiguous cold and warm areas; it

---

Note that he no longer calls it a "supposed" ridge; so certain was he, that thesis had practically turned into fact.

is evident that he was at some pains to install a donkey engi
for this purpose on board the KNIGHT ERRANT, a ship "quite u
suitable for such work" (49).

Monday

My dear Tizard,

I am very glad that arrangements are so forward. We shall easily man
details I have no doubt.

1st as to the Engine. What is the tonnage of the Knight Errant?
there space on her deck for an engine and boiler measuring 10 ft by ab
3 ft 6, for if so I can get one easily. If not would there be any difficu
in connecting the main boiler with a small donkey engine? In either c
I have no doubt the thing can be easily managed.

2 As to rope & gear, I have written to Admiral Richards about the w
dredging rope and will see to having some of it. In case of accidents howe
would they give us do you think a thousand fathoms or so of whale lin

3 What became of the dredges on board the Challenger? Could we
get some of them out of that? I have written to Plymouth to Heardon
for a couple of 10 ft beam trawls, ready for use, and if we can't get t
old ones I will set to work at once and have some new dredges ma
The dredge-bags are the great difficulty. I wish we had some of the
'Challenger' ones. I will take care and not have a troublesome quant
of spirit Of course I look upon the dredging in this case as purely seconda

4. I have plenty of thermometers and I am at present getting Tait
give me the exact pressure error of half a dozen of them. I have about

The Hydrographer told me that he meant to send one of Sir W. Thomso
wire sounding affairs, so I have done nothing about that.

What I would like to ask for is a little additional dredging rope, a
some of the old dredges with their bags. All the rest I think I can man
myself.

The strain will not be great at these small depths, but on hard grou
there is always the chance of losing the dredge or trawl. I would like
or two of our large light dredges, as well as some small ones. Had we
better also get some of the water-bottles? I doubt if the results are wo
much at these depths, but it would be well not to lose them. . . . . .

Yours vy tly
C. Wyville Thomson

The "Sir W. Thomson" mentioned above is Lord Kelvin (182
1907), British mathematician and physicist, professor at Glasgo
while known particularly for his studies in electricity, he is perha
less well remembered for his part in laying the Atlantic cables (5
(51) and for devising a sounding apparatus.

Bonsyde
Linlithgow, N.B.
Monday

y dear Tizard,

I have written to Heardon (?) for two trawls, and I will do nothing about edge ropes till I hear from Capt Evans. As to Hydrometers we have still ose used by Buchanan on board the Challenger, and we have also his paratus for boiling out the gases. I do not know if we can by any pos-ility perform that operation. I would like to have it done if possible, d I have sent Frank to Dr. Crum Brown to practice a bit. I am not sure at he is up to the work however.

Thanks many about the cots. Suppose you let me know by telegraph enever you arrive and I will see you at once at Greenock. Say Saturday rning. I would not be sorry if you had to put off till the beginning of e next week for I shall have enough to do to get ready. At all events I ll run through whenever you arrive & see how everything looks. Then u might come here for a day, if you could leave the Knight.

Yours vty
C. Wyville Thomson

Frank" in this letter is Sir Wyville and Lady Thomson's only d, who subsequently entered the Indian Medical Service (52). omson, writing about the Faroe Channel cruise of the KNIGHT RANT, says, "... the civilians who accompanied Capt. Tizard e Mr. Murray, our indefatigable assistant Mr. Frederick Pearcey, h my son as a supernumerary" (49). Alexander Crum Brown is well-known Scottish chemist of the period.

Bonsyde
Sunday

y dear Tizard,

The little chart seems in every way excellent. Your demand for a name r the ridge stumped us a little, but after a little hunting I have got a ame which I think will do The "YMIR" ridge. "YMIR" was a giant of e Scandinavian Mythology who after his death was cut up into the earth the sea, and the heavens but during his life he had the peculiarity of ving one side always hot & the other side always cold, hence the pro-riety of the use of him as a God-father.

Did not we agree that it would be well to have another Table giving l the temperatures from 1500 fathoms to the bottom? I do not suppose at much importance goes with this but I suppose all the observations f all kinds should be printed.

So far as I see we have only the temperatures down to 1500 for t whole course and the bottom temperatures.

I am getting on with my work about the Faroe Channel and I hope have it done by Xmas. Heavy snow Bar: 28.5 in.

Yrs vy ty
C. Wyville Thomson

You will get the chart back from Murray by next post if you have r got it already.

The cruise of the KNIGHT ERRANT was over, the ridge separati the cold and warm areas had been established, and Tizard a Murray were preparing to write their paper (46) on the subject hence the request for a name (see below).

Sir Wyville had joined the ship at Oban on 22 July, had proceed with her to Gairloch and thence to Stornoway; save for his retu to the mainland this was Thomson's last sea voyage. He did n go with the KNIGHT ERRANT on her four traverses of the Far Channel between 24 July and 20 August, although he did rema at Stornoway to direct operations. Herdman (7) writes: "The resu completely justified Sir Wyville Thomson's prediction, and show that a ridge rising to within 300 fathoms of the surface runs fro the N.W. of Scotland by the Island of Rona to the southern e of the Faroe fishing banks."[11]

The dredging operations were not very successful, "owing to t boisterous weather and insufficiency of the vessel" (49). Howev in the summer of 1882, after Thomson's death, Tizard and Murr undertook a further exploration of the area on H.M.S. TRITON, "whi was very fruitful of zoological results." Thomson's concern abo getting ". . . a few casts of the trawl on each side of the line . . were more than borne out. "The warm area was found to have 2 species, while the cold had 217, and of these only 48 species we common to both . . . a notable example of the effect of the enviro ment on the distribution of marine forms of life" (7).

Thomson's suggested name for the ridge is most apt. Carlyle 1840 wrote as follows: "The Gods, having got the Giant Ymer slai a Giant made by 'warm wind,' and much confused work, out the conflict of Frost and Fire,—determined on constructing a wor

---

[11] There is a nice modern account of the hydrography of the Faroe Channel Tait (53).

n him. His blood made the Sea; his flesh was the Land, the
ks his bones; of his eyebrows they formed Asgard their Gods'-
lling; his skull was the great blue vault of Immensity, and the
ns of it became the Clouds. What a Hyper-Brobdignagian
ness!" (54).[12] Despite the propriety of Ymir as a name, Tizard
Murray (46), in a paper communicated on 15 May 1882 to the
al Society of Edinburgh, chose to call the submarine elevation
ville Thomson Ridge—the name it bears to this day (53).

Bonsyde
Linlithgow, N.B.
Dec. 1st 1881

y dear Tizard

In the first place let me congratulate you heartily on the cause of your
sit to London & pray give my respects to Mrs. Tizard whose acquaintance
hope to make later on.

Next I do not quite see why Mr. Malby has changed his plan. I was
st going to write you about this chart, for now that I have given up other
ork I need the sheet very shortly. Only I think it might be done in this
ay. Let Malby cast off say 20 copies Let us see these and go over them
once (send some to you and some to me) and then at once go on to the
50. I will however write to the Controller if necessary & see if this plan
approved if you think it necessary—at all events 750 copies will be re-
uired or perhaps 800. I will ask the Controller about that.

What about the printing off the remainder of the diagrams. I do not
ink we have got them yet.

I suppose you have been getting the volumes as they appeared Is not
e last one Vol III a beauty?

Yours very truly
C. Wyville Thomson

his letter was written a little more than three months before
omson's death. He was well enough to have been in the chair
meeting of the Royal Society of Edinburgh on 6 June 1881 and
have communicated a paper on the physical and biological con-
ons of the Faroe Channel on that date (56). However, he had
met with his classes at the University for several sessions, and
f. Alleyne Nicholson of St. Andrews conducted them on his be-
f during the summer (57). The 3 November issue of *Nature* says
t "Sir Wyville Thomson has not yet resigned the chair of Natural

---

YMER was also the name of a Norwegian expeditionary vessel during the period
hese letters (55).

History in Edinburgh University, though we regret to learn th he is likely to do so in a few days" (58); hence the reference in t letter to having given up other work. However, it is evident th with great gallantry he tried to continue on with the CHALLENG work to the last, and it was not until after his death that Jo Murray "was entrusted by the Government with the direction the whole of the work" (11).

The content of the first paragraph has to do with Captain Tizar marriage. Born in 1839, he was married in 1881 to Mary Elizabe daughter of W. H. Churchward, C. E. Tizard died in 1924.

CONCLUDING REMARKS

These letters illustrate the vast extent of Sir Wyville Thomso correspondence. His accomplishments between 1876 and 18 despite ill health much of the time, were remarkable, and the co pass of his publications is not generally appreciated. Herdman, w knew him through the eyes of a younger man, was moved to wr of him in 1923:

> It is unfortunate that the man of science has so frequently to mak choice between the necessary work of administration and original resear Let us trust that he does not invariably select the work for which he least fitted. Sir Wyville Thomson was given little time for either. In t few years of work that remained before his health gave way, he was occupied with his many and varied duties as director of the Commissi and editor of the reports, that there was little time for the original w he had planned to do in connection with the collections of Stalked Crino and of Hexactinellid Sponges—the two groups that he had reserved his own investigation, and upon which he was an acknowledged authori . . . He was a man of handsome presence and genial nature, with gr personal charm of manner. His general culture, large fund of informat on many subjects, his aptness and humour in conversation all contribut to make him a social success in Edinburgh and the beau-ideal of a h in his country home, where he gathered round him a large circle of frie by no means confined to scientific men.
>
> He had a quaint way of occasionally bringing in old Scots sayings, snatches of poetry, as for example, when he thought a question uni portant:—
>
> Twenty peacocks in the air. I wonder
> how they all got there. I don't know—
> and I don't care!
>
> or—more briefly, when with friends who understood him, simply—"Twen Peacocks." (7).

is a source of great pleasure to write for the Thomas G. Thomp- Anniversary Volume. When the senior author arrived at the Uni- ity of Washington in September 1932, the first person he met Dr. Thompson; through two years in Seattle, "Tommy" Thomp- kept a weather eye on him, academically and otherwise. There d have been no better mentor.

e cannot conclude without acknowledging the help of many colleagues in preparing the details of this article, particularly: s P. Curtis, C. Beecher Hogan, Anne R. Kinloch, Herman W. ert, Robert F. Metzdorf, Yngve H. Olsen, and Rulon Wells.

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HE RELICT FAUNA OF LAKE MERCED, SAN FRANCISCO

By

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ABSTRACT

Merced, formerly connected with the Pacific Ocean by a channel which
sed sometime between 1869 and 1894, is now a freshwater lake with a char-
tic freshwater fauna, except for five species of definitely marine affinities.
represent three phyla and five major subgroups (classes or orders), as follows:
lophora lacustris Allman (Colenterata, Hydroidea); *Neanthes limnicola* (John-
Annelida, Polychaeta); *Neomysis mercedis* Holmes (Crustacea, Mysidacea);
haeroma oregonensis (Dana) (Crustacea, Isopoda); *Corophium spinicorne* Stimp-
Crustacea, Amphipoda).

of these are considered to be relict species which survived the change of the
from brackish to fresh water, with the probable exception of the hydroid *Cor-*
hora lacustris, which was first noted in the lake in 1946 and which seems likely
of recent introduction.

ake Merced is an irregularly-shaped body of water, approxi-
ely two miles in length and some 350 acres in area, lying within
city limits of San Francisco about a quarter of a mile from the
n beach. It has a maximum depth of about 30 feet and its bot-
is below sea level. It was formerly connected with the ocean,
within historic times it has become a freshwater lake which is
as an auxiliary reservoir of the San Francisco water system.
he lake is fed by the runoff, mostly underground, from an area
bout five squares miles, and as a reservoir it is considered cap-
of yielding around 400 million gallons a day. The chlorinity,
rding to records of the San Francisco Water Department, based
samples taken at approximately weekly intervals from August
7 through July 1958, ranged from 0.72 to 0.98 $^{0}/_{00}$, with an average
.92. This small fluctuating salt content, which shows no definite
tion to season, may be due to wind-borne salt or to seepage
the adjacent ocean.

oologists acquainted with Lake Merced have known for many
rs that, in addition to the usual population of organisms char-
ristic of freshwater lakes, it contains an interesting group of

relicts that do not occur in other nearby lakes and that appea
have survived from the time when the lake was connected with
sea. Strangely, there has been almost no mention of this in
literature. The only account of it known to me is that by John
(1903), who discusses the origin of the lake, speaks of "the ma
forms found" in it, mentions four of them, and then proceeds
describe one of the four as a new species of *freshwater* polycha

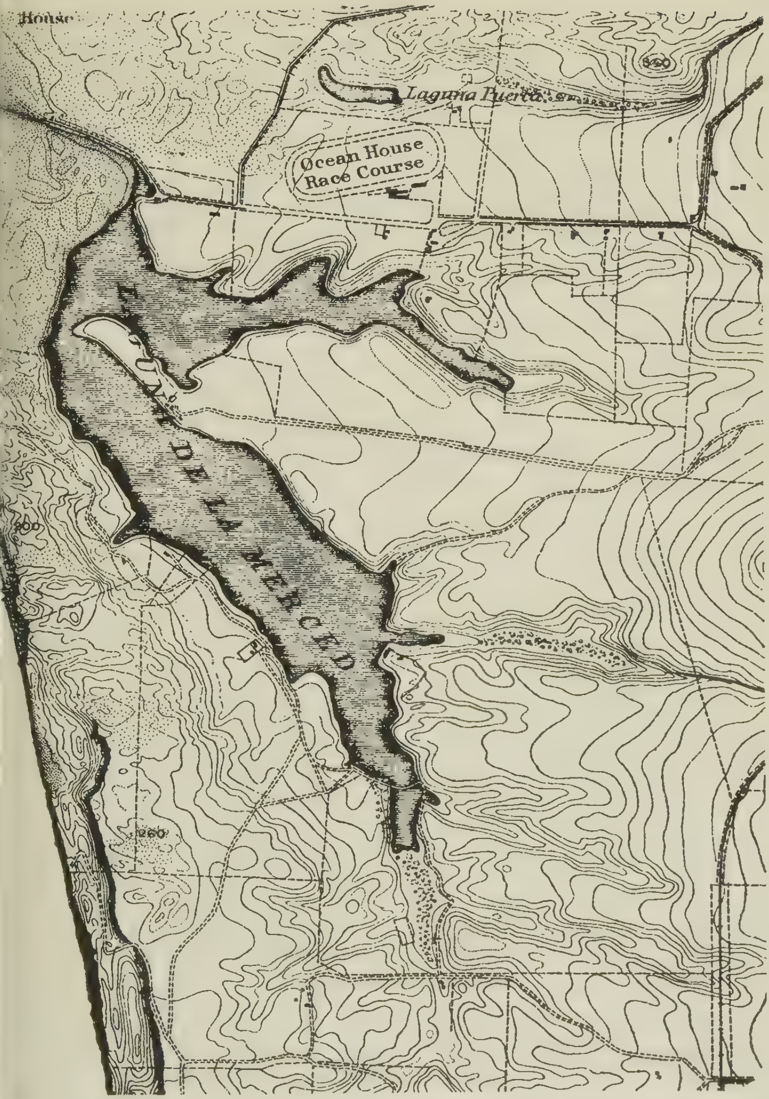
It seems desirable to make all that is known about Lake Mer
and its relict fauna a matter of record because of the rapid
radical changes that have been made in the environment in rec
years. The lake has been treated with rotenone to destroy ro
fish and has been stocked with rainbow trout; it has also b
treated with copper sulfate on occasion to control the growth
algae. This type of management, however important to the pres
multipurpose use of the lake (fishing, boating, and water stora
does not commend itself as a means of preserving the origi
fauna. It will be interesting to see whether species that have s
vived the transition from a salt- or brackish-water environment
one of fresh water will be able to withstand the environmen
pressures of scientific management.

HISTORY OF THE LAKE

Lawson (1895: 474) has stated in part regarding Lake Merc

> ". . . This lake is a remarkable feature of the topography. It lies i
> depression which is a structural valley and which is separated from
> ocean by a very narrow ridge. Though thus lying in a structural vall
> the form of the shore contours of the lake, the stream cliffs by whic
> is bounded, and its relation to the drainage of the valley all demonstr
> that the immediate basin of the lake is a drowned valley of stream erosio
>
> "The bottom of Lake Merced is 10 feet below sea-level, and this f
> demonstrates a recent submergence. The drowned valley undoubtedly
> free access to the ocean at tide level, but sand dunes choked the chan
> and dammed back the waters till they stood 10 feet above tide. Si
> then the level of the lake has been artificially raised another 10 feet .
> The lake is certainly one of the most recent topographic features of
> field, and suggests that subsidence is now in progress."

Johnson (1903) has quoted Lawson in a personal communicati
"the date of the invasion of the salt water was in late Quatern
time." Lawson does not indicate when the connection was terminat
but this can be ascertained with an accuracy of 25 years or l


House
Laguna Puerca
Ocean House Race Course
LAGUNA DE LA MERCED
340
200
260

ure 1. Lake Merced as shown on a U.S. Coast and Geodetic Survey map dated 1869.
channel leading to ocean).

A U.S. Coast and Geodetic Survey map of the San Francisco pe insula dated 1869 shows a tidal channel between the north end Lake Merced and the ocean beach (Fig. 1) along the approxima course now followed by Sloat Boulevard. This channel was clos before Lawson wrote his 1895 paper (based on work done in 1893– and probably before he began his geological work in California 1890. A map published in the magazine Zoe for January 18 shows the channel to the sea still open, but I think it should disregarded, since it is a crude map and is doubtless copied or trac from an earlier one. If the channel had really been open as late 1892 it is inconceivable that Lawson would not have known it.

Inasmuch as Lake Merced catches the run-off of a fair-siz drainage basin and is also fed by underground springs, it is like that, during its connection with the ocean, fresh water dominat the situation, at least seasonally during winter rains and perha throughout the year except during extremely dry periods wh evaporation might have combined with tidewater to increase t halide content. I visualize Lake Merced during its maritime peri as a rather strenuous environment, with incursions of salt wat at high tide, extrusions of surface fresh water at low tide, so layering but considerable mixing due to winds and the relati shallowness of the lake, and seasonal variations due to fluctuatio in rainfall. This is the kind of situation in which euryhaline spec become the dominant population. It is quite likely that the rel species of Lake Merced are the ones that first became establish there when this drowned valley was invaded by the sea.

Since Lake Merced became a freshwater lake, there have be man-made changes of considerable magnitude. Originally it was single lake consisting of a north arm and a south arm connect by a narrow channel, but now it is really two lakes separated an earth-fill dam. This dam, which might more properly be call a causeway, was constructed in 1897, presumably for convenien in crossing a body of water that would require a long trip aroun The north and south lakes are connected by an underground pi with a valve which is generally kept closed except when it becom necessary to equalize the water levels. No study has been made to whether this nearly complete separation of the two sections h resulted in any changes in their respective biota; but the commer

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[1] Volume 2, Number 4: pl. 17.

his paper regarding the fauna pertain especially to the south , which is the larger.

am informed by Mr. Harry W. Tracy of the San Francisco er Department that the lake level was formerly 22.10 feet above level but that it was lowered in 1952 and has since been main- ed at 20.5 feet. There is an overflow tunnel from the south to the ocean; but the differences in level render the probabilities vasion of marine organisms by this route rather small.

THE RELICT FAUNA

omysis mercedis, a crustacean of the order Mysidacea, was ribed by Holmes (1897) on the basis of specimens collected in Merced by H. P. Johnson in 1895. It has since been found ly distributed on the Pacific Coast in brackish-water bays and aries from San Francisco Bay to Vancouver Island (Tattersall,). Its range frequently extends into fresh water, but it does appear to have been recorded in any situation which it could have reached from the sea. It is still abundant in Lake Merced. ottle containing several hundred specimens was brought to the demy for identification in October 1958.

eanthes limnicola was described from Lake Merced as *Nereis icola* by Johnson (1903), who, as already mentioned, described s a freshwater species. If, as suggested by Smith, *et al.* (1954), conspecific with *Neanthes lighti* Hartman (1938), then it is a haline species occurring in brackish water environments at ous localities along the Pacific Coast. Otherwise it is known only n the type locality, where it still occurs. Several specimens re- ly brought to the Academy for identification had been taken n the stomach of a trout caught in Lake Merced, 22 June 1957.

xosphaeroma oregonensis (Dana), an isopod crustacean, was re- ed from Lake Merced by Johnson (1903) on the basis of infor- ion supplied by Holmes. Robert T. Orr, now on the staff of California Academy of Sciences, collected it there in 1932 and rts (personal communication): "Individuals were found to in- it the crevices of old sunken logs and smaller pieces of wood h were present along the lake shore." This corresponds to ations in which it is found at various localities around San ncisco Bay. I do not know of any recent reports of this species from Lake Merced, but it is a durable organism and is unlikely have died out.

Corophium spinicorne Stimpson, an amphipod crustacean of wi distribution in salt and brackish waters on the Pacific Coast, w also reported from Lake Merced by Johnson (1903) on the authori of Holmes. This species was likewise collected by Orr (perso communication) in 1932. Shoemaker (1942) reported the curic fact that *C. spinicorne* had been taken "from the water supply the city of San Francisco." Subsequently Shoemaker (1949) clarifi this by explaining: ". . . a male specimen was sent to the U National Museum in 1924 from the fresh water of the water syst of the city of San Francisco, Calif., where it was said to be qu numerous. On April 5, 1936, males and females were taken by A. Ek berg in Merced Lake, where the species is said to be abunda The water supply of San Francisco was partially drawn from t lake in 1924, so that it is quite probable that the male sent to t National Museum at that time came originally from the lak San Franciscans who may not care for *Corophium* in their drinki water can be reassured; at present Lake Merced water is used o for irrigation, principally of the adjacent golf course.

Cordylophora lacustris Allman, an athecate hydroid, was record from Lake Merced by Hand and Gwilliam (1951) on the basis information supplied by me. In 1946 I was called on by the S Francisco Water Department to identify a hydroid that had beco so abundant in Lake Merced that it was fouling the bottoms boats, and there was fear that it might clog water pipes. This spec proved to be *C. lacustris*, a well-known euryhaline species of wi distribution (Europe, Atlantic Coast of North and South Ameri New Zealand, Australia, China, etc.). It had not been report previously from the Pacific Coast of North America, but, by interesting coincidence, Fraser (1946) predicted its probable appe ance on this coast the same year it was found in Lake Merc However, according to Professor Trevor Kincaid of the Univers of Washington (personal communication), it was well establish in Lake Union, Seattle, as early as 1920.

It is a good question whether this is a relict or a newly introdu species in Lake Merced. Not unnaturally, when I first found i considered it another member of the relict fauna. But in the sa year that I found it in Lake Merced it was found by the late P r Harold Kirby, JR., of the University of California, in the mond filter plant of the East Bay Municipal Water District sonal communication) and subsequently in the San Joaquin r at Antioch (Hand and Gwilliam, 1951). This species tends e sporadic in abundance and may easily have been overlooked n it was not numerous. On the other hand, it seems improbable it could have been present in Lake Merced and have escaped e during the half century or more that this lake has excited nterest of naturalists. The weight of evidence seems to favor dea that it is a recent introduction; but how it got in Lake ed is an interesting problem. The overflow tunnel from the h lake to the ocean is a possible though not very likely avenue.

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TRIBUTION OF MAN-MADE RADIOACTIVITY IN THE NORTH PACIFIC THROUGH SUMMER 1955

By

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ABSTRACT

radioactivity which originated from the Bikini and Eniwetok tests in the
of 1954 was transported mainly to the west, then to the north toward the
of Japan, and finally down south along the Kuroshio Current by summer
. Activity in contaminated areas where activity in sea water was greater than
c of Sr^{90}/l averaged 4.2×10^6, 1.9×10^7 and 2.7×10^7 km^2 respectively in
1954, March–April 1955, and August–September 1955. In spring 1955 the
ity extended down to about 600 m below the surface. Vertical distribution of
nuclides might be influenced less by vertical migration and decomposition of
ne life than by physical mixing. A horizontal eddy diffusion coefficient of 0.8–
10^9 was obtained from the time change of distribution of radioactivity in the
n.

arge scale contamination of the ocean due to man-made radio-
vity was confirmed during the first Japanese Bikini Expedition
yake, *et al.*, 1954), conducted aboard the observation ship
NKOTSU-MARU in May and June 1954. This expedition was under-
en about one month after Castle Test at the Bikini-Eniwetok
ving ground in spring 1954. In sea water, maximum activity of
00 dpm/l was found 450 km west of Bikini, and activity of more
n 1,000 dpm/l was distributed as far as 2,000 km WNW of
ini along the North Equatorial Current. In plankton the highest
ue was 800,000 dpm/g wet weight.

rom 25 February to 3 May 1955, the U.S. Atomic Energy Com-
sion, in co-operation with Scripps Institution of Oceanography
the Applied Fisheries Laboratory of the University of Washing-
(U.S. Atomic Energy Comm., 1956), carried out a transoceanic
edition in the Pacific aboard the U.S. Coast Guard Cutter TANEY
the purpose of measuring radioactivity. Results showed that
er activity than that observed previously, ranging from 0 to
dpm/l in sea water and from 3 to 340 dpm/g wet weight in
nkton, was diffused over a larger area than before. The highest

activity was located off the coast of Luzon Island in the Philippi and some activity still remained in water along the North Equato Current. In summer 1955, the North Pacific Expedition (NORPA carried out through international co-operation of Canada, Japan United States, found that slight (0–30 dpm/l) but wide-spr activity remained in the water in a large part of the western No Pacific, maximum activity being observed along the Kuros Current off the coast of Japan.

Again, from May to July 1956, about ten nuclear tests at Bikini and Eniwetok area brought about further contamination the Pacific. According to results of the second Japanese Bik Expedition (Fisheries Agency, Japan, 1956), conducted from May to 30 June 1956, the activity in sea water was lower t that in 1954 by a factor of ten. These lower values resulted from facts that the observations were made during an earlier stage of test series and that the observation points were located more t 900 km from the test site as compared to those in 1954. Also, m of the explosions took place at a higher altitude than in 1954, wh diminished the direct contamination of the sea surface. Howev note that considerable activity was found not only along the No Equatorial Current but also in the region of the Equatorial Coun Current, where little activity had been observed in 1954. Accord to observations, there was a remarkable correlation between activity of falling dust on the deck and in the sea. Therefore, c tamination of the sea water in May and June 1956 may well h been due mainly to direct fall-out of air-borne dust rather than transport of contaminated sea water from the test area by oc currents.

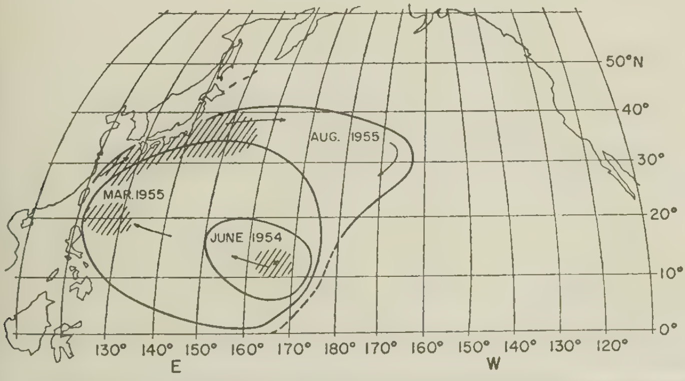
In July and August 1956, the Equatorial Pacific Expedit (EQUAPAC), undertaken by oceanographers of Canada, Fran Japan and United States, found that radioactivity was concentra in the sea area of 5–15° N and 145–165° E. The highest activi 193 dpm/l (evaluated one year after sampling), was found n 10° N, 160° E. Only a trace of fission product was detected eit in the area south of the Equator or east of 180° W. In Septem 1956 a survey of radioactivity was made by the U.S. Atomic Ene Commission in collaboration with the Applied Fisheries Laborat of the University of Washington (U.S. Atomic Energy Comm., 19 in an area bounded by 09° and 15° N and approximately 145° a 166° E. The highest value for water activity was 19,000 dp

LE I. RADIOACTIVE CONTAMINATION IN NORTH PACIFIC WATERS (1954–1955)
UNIT: $\mu\mu c$ Sr^{90}/l

	Period	*Contaminated Area where Activity was >0.1 μμc/l*	*Maximum Activity Observed (μμc/l)*	*Maximum Average Activity of Water Column (μμc/l)*	*Average Activity as Sr^{90} (μμc/l)*	*Total Amount of Sr^{90} (mega C)*
KOTSU ition	31 May– 30 June 1954	4.2×10^6	194* 11°05′ N 160°12′ E 80 m	45* down to 100 m	7* down to 100 m	2.6 + X
ation	9 March– 13 April 1955	1.9×10^7	3.9 21°30′ N 124°45′ E 0 m	1.8 down to 400 m	0.4 down to 400 m	3
AC dition	August– September 1955	2.7×10^7	0.5 28°25′ N 129° E 0 m	0.5 down to 500 m	(>0.1) (<0.1) 0.2 0.03 down to 500 m	3**

xcept near the test site.

n which 0.1 Mega Curie of Sr^{90} is attributed to fall-out. Contribution of fall-may be about 0.5 Mega Curie at present, which is equivalent to 0.02–0.1 $\mu\mu c$/l rding to depth of contaminated layer.



gure 1. Radioactive contamination in the North Pacific. Shaded areas represent those aximum contamination.

between Eniwetok and Ujelang, and the lowest value was 48 dpm northeast of Bikini; the highest value in plankton, 21,000 dpm wet weight, was found about 1,300 km north of Eniwetok, and lowest value, 27 dpm/g, was obtained near Guam.

In this study of radioactive contamination in the North Pac through summer 1955, the activity in sea water was converted the value of Strontium-90 (assuming that Hunter-Ballou's table applicable) in order to make the activities comparable with ea other. Results are summarized in Table I and Fig. 1. As shown Fig. 1, the activity which flowed out from Bikini was transpor mainly to the west, then to the north toward the coast of Jap and finally down south along the Kuroshio Current. Note that contaminated area is located mainly in the western half of North Pacific.

Vertical distribution of radioactivity in sea water is shown Figs. 2 and 3. Fig. 2 shows that in June 1954 it was limited to mixed layer above the thermocline. In March 1955, however, activity extended down to about 600 m below the surface, thermocline being present at a depth of 75 m.

According to Steemann Nielsen (1952), organic productivity the sea, expressed as grams of fixed carbon per square meter, 0.2 g C/day/m^2 or 73 g C/year/m^2 in the tropical Pacific. If thickness of the euphotic zone is assumed to be 100 m, then rate of formation of organic matter in a year is only 0.7 mg C/l about 2.7 mg/l of planktonic organisms. Assuming that enrichment factor of radionuclides in marine organisms is 10^3,

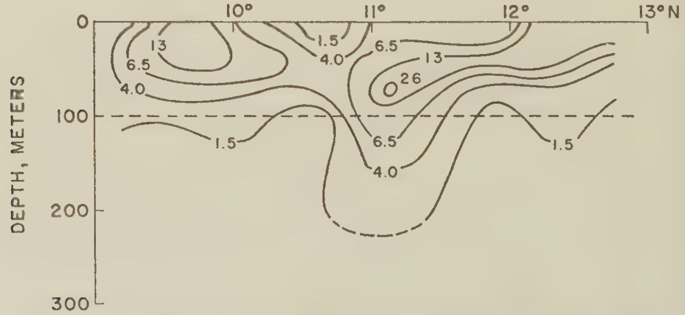
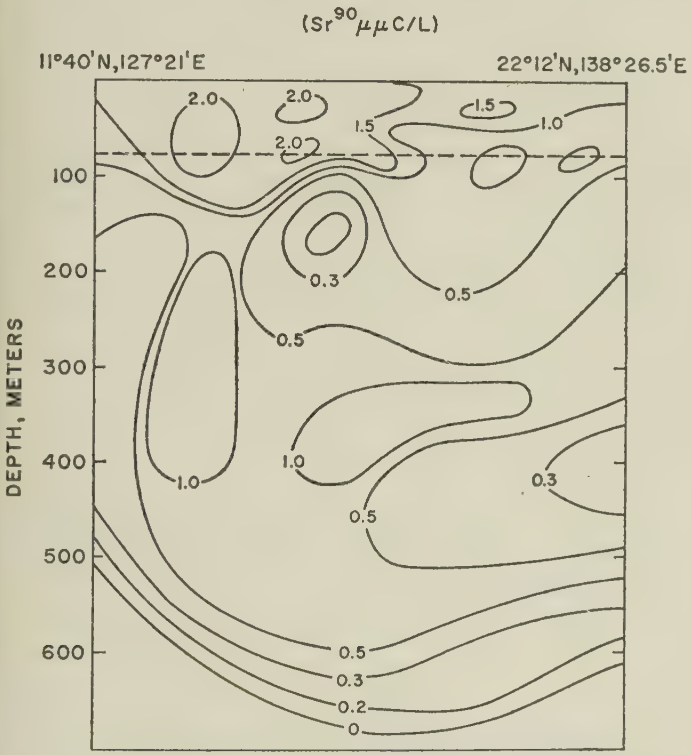


Figure 2. Distribution of radioactivity in sea water on a vertical section perpendic to the North Equatorial Current along a line 570 km west of the Bikini Atoll, June 1 The thermocline is shown as the broken line (unit, $\mu\mu c$ of Sr^{90}/l).

ion of activity in organisms is only 0.3 $^0/_0$ of that in sea water.
efore, decomposition of sinking marine life may not be the
e of contamination of sea water below the thermocline.



gure 3. Vertical distribution of Sr^{90} in the North Pacific, March 1955. The thermo-
is shown as the broken line (unit, $\mu\mu c$ of Sr^{90}/l).

s to the effect of migration of organisms upon transport of easily
le elements, Ketchum and Bowen (1958) gave the following
ation:

$$\frac{T_B}{T_P} = V_0 \frac{f_0}{A_z} \cdot \frac{d \cdot d_m}{t},$$

re T_B and T_P are the biological and physical transport respec-
ly; V_0 the volume of organisms per unit volume of water; f_0
ratio of concentration of the element in the organism to the

total concentration in the water; A_z the vertical coefficient of edd diffusion; d the depth of the gradient zone; d_m the distance ove which the organism migrates; and t the period of migration. Miyosh (1956) gave about 5 to 10 $\mathrm{cm}^2/\mathrm{sec}$ as the value of A_z near the Bikir area. Assuming that V_0 is 1×10^{-6} (1 cc of wet plankton per cubi meter of sea water), that both d and d_m are 100 m, and that t i 10^5 sec, the ratio T_B/T_P will be 0.1–0.2 when the enrichment facto is 10^3. Thus, if there is any biological transport of radioactive materia in a vertical direction in sea water, the migration of plankton migh be more effective than decomposition of organic matter in transporting radioactive material, although it would be only 10–20 $^{0}/$ of the physical mixing rate.

When radioactive material diffuses out from a source point, th horizontal eddy diffusion coefficient may be obtained from the tim change of the distribution of the activity. The relation between th eddy diffusion coefficient k, time t, and the lateral distance Y fror the centre of diffusion, is as follows:

$$Y^2 = 2\,kt.$$

TABLE II. Horizontal Eddy Diffusion Coefficient Calculated from th Time Change of Distribution of Radioactivity in the Ocean

t (days)	Y (km)	k
60	890	0.8×10^9
270	2100	1.0×10^9
420	3200	1.4×10^9

From the observed values of Y and t, the value of k was calculate and is given in Table II.

According to Inoue (1950), the horizontal eddy diffusion coefficient k for oceanic turbulence may be expressed as follows:

$$k = 0.01\ L^{4/3} \qquad (10^{10}\ \mathrm{cm} > L > 10\ \mathrm{cm}),$$

where L is the magnitude of diffusion phenomena in the ocean.

By putting the value of k into the above equation, $\log L = 8.1-8.$ was obtained, which corresponds with the observed value of $\log Y =$ $7.9-8.5$.

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THE (ETHYLENEDINITRILO)TETRAACETATE TITRATION (CALCIUM AND MAGNESIUM IN OCEAN WATERS[1]

I. DETERMINATION OF CALCIUM

By

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ABSTRACT

Various factors influencing the determination of calcium in ocean water (ethylenedinitrilo)tetraacetate titration have been investigated. Using Cal-Red indicator, the method has been applied in titrating 36 ocean samples. A calciu chlorinity ratio of 0.02134 was obtained. The speed, preciseness, accuracy and si plicity of the method should encourage its future use.

INTRODUCTION

Ocean water is a complex solution of ions, with sodium and chlori predominating and with sulfate, magnesium, calcium and potassiu comprising the other major ions. Most of the other known chemic elements occur in ocean water in minor or trace quantities. Althou the total concentration of ions in ocean water varies with localit it has been amply proven that the relative concentrations or rati of the major ionic species and of some minor ones remain surprising constant. Since the chloride ion is predominant and since it may determined readily and with great accuracy, the concentrations other ions are frequently reported as ion-chlorinity ratios.

Although all of the alkaline earths occur in sea water to son degree, only magnesium and calcium are major constituents; stro tium is present in minor but significant quantities. Analyses ocean waters for these ions have not been numerous but they ha yielded metal ion-chlorinity ratios which have been quite constan However, the exact values of the ratios have not been establishe with certainty; furthermore, there is some doubt as to wheth

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ations of individual samples from the average ratio have sig-
ance or are due to experimental errors in analysis. The methods
nalysis which have been used for both calcium and magnesium
ea water, in general, are laborious and subject to important
rs. Certainly fast and accurate methods of analysis would be
ly desirable. Recent use of (ethylenedinitrilo)tetraacetate (con-
ently designated EDTA) as a complexometric titrant in esti-
ing calcium and magnesium has suggested its application to
ysis of sea water.

arpenter (1957b) has reviewed concisely the methods which
been used in analyses of ocean water for calcium. Previous
stigators have most frequently precipitated the calcium as the
ate and weighed it as calcium oxide or estimated it with po-
ium permanganate titration. The calcium oxalate method is
icularly susceptible to errors due to coprecipitation of sodium,
assium, magnesium and sulfate. Also, it has been generally as-
ed that strontium was completely precipitated and estimated
n calcium. If the strontium content is known, then the calcium
tent can be readily calculated. But recently certain experimental
lence by Carpenter (1957b) and Banewicz and Kenner (1952) has
icated that the strontium may be only partially precipitated,
ving it uncertain as to what correction should be applied to
ain the calcium content. A flame photometric procedure for
mating calcium, with an indicated precision of about one per-
t, has been reported by Chow and Thompson (1955b). Since
cium is measured directly by this method, no correction need be
de for strontium.

e Sousa (1954) has indicated satisfactory results in estimating
cium in ocean water by titration with EDTA, using murexide
he indicator, but he included no data in his paper. Voipio (1957),
estimating magnesium in Baltic Sea waters, determined the al-
ine earth metals, but, like de Sousa, he gave no data. Carpenter
57a, 1957b) also determined calcium in sea water with EDTA
ation, but he used a spectrophotometric titration technique to
ablish the end point. Before titration, Carpenter separated calcium
n magnesium by ion-exchange chromatography. al Kadhim
57) titrated sea water for calcium with EDTA after separating
calcium from the magnesium by precipitating calcium oxalate.
s work was of a preliminary nature but appeared promising.
ommonly used method of estimating calcium in natural waters

(Diehl, *et al.*, 1950) involves titration of calcium with EDTA af precipitation of magnesium as the hydroxide at pH 12. The co plexometric titration of calcium in sea water is faster and it off the possibility of being more accurate and precise than the gra metric or volumetric procedures which depend on calcium oxal precipitation.

REAGENTS AND INDICATORS

Unless otherwise indicated, all chemicals except indicators w reagent grade.

Calcium Standard Solution. Mallinckrodt's calcium carbona analytical reagent (containing 0.01 $^0/_0$ Mg and 0.01 $^0/_0$ alkali as s fate) was used in preparing the calcium solution.

Dissolve 1.001 g of calcium carbonate, dried at 105° C, in a mi mum of 2 N HCl and dilute to about 600 ml. Dissolve 12.3 g reage grade magnesium sulfate heptahydrate ($MgSO_4 . 7H_2O$) in the soluti and dilute to one liter in a volumetric flask.

(Ethylenedinitrilo)tetraacetate Solution. Dissolve 5.585 g of reage grade disodium dihydrogen (ethylenedinitrilo)tetraacetate dihydra in water and dilute to one liter to obtain a 0.01500 M solution. U it either as a primary standard (Blaedel and Knight, 1954) or stan ardize it against the standard calcium solution.

Sodium Hydroxide-Potassium Cyanide Solution. Dissolve 80 g sodium hydroxide and 10 g of potassium cyanide in 500 ml of dist led water and dilute to one liter.

Cal-Red Indicator [1-(2-hydroxy-4-sulfo-1-naphthylazo)-2-hydr xy-3-naphthoic acid]. This indicator was obtained from Scien Service Laboratories, Inc. Dallas 21, Texas. Triturate 0.5 g of t indicator with 50 g of sodium sulfate until the dye is evenly d tributed throughout, as recommended by Patton and Reeder (195

Other indicators investigated in this paper were prepared directed in the literature cited.

Calcein. Its structure has not been established. It is a condensati product of fluorescein, formaldehyde and iminodiacetic acid; Di and Ellingboe (1956).

Calcein-Thymolphthalein; Tucker (1957).

Erio R, Eriochrome Blue-Black R, Calcon; Sodium salt of 1- hydroxy-1-naphthylazo)-2-naphthol-4-sulfonic acid; Hildebrand a Reilley (1957).

io SE, *Eriochrome Blue SE*; Disodium salt of 3-(5-chloro-2-
oxyphenyl-azo)-4,5-dihydroxynaphthalene-2,7-disulfonic acid;
ard, *et al.* (1956).
urexide; Ammonium purpurate; APHA (1955).
urexide-Naphthol Green B; Knight (1951).

PROCEDURE FOR CALCIUM

et 25 ml of the sea water sample into a 125 ml flask and dilute
ml. From a 50 ml buret, deliver 1 ml less than the required
nt of the titrant as calculated from the chlorinity value (a).
the sample and add 5 ml of the sodium hydroxide-potassium
ide solution (b). After three to five minutes add 0.5 g of Cal-
indicator (c) and titrate (d) to a blue end point (e).

. This volume can be ascertained from preliminary titration of
parate sample if it is expected to have an abnormal calcium-
rinity ratio.

). Potassium cyanide is added to the sample solution to complex
traces of metals which might block the proper functioning of
indicator.

). This amount of indicator can be measured easily with an
opriate measuring spoon.

). Magnetic stirring is recommended.

). Comparison should be made with an appropriate reference
tion.

INVESTIGATION OF THE METHOD

ior to analysis of sea water samples by complexometric titration,
erous indicators, buffers and procedural modifications were
stigated exclusively before arriving at the procedure described
. A brief summary of this investigation follows.

atistical Treatment of Results. When investigating the various
ts in the method, titrations were made on a group of identical
ples, usually five or more in number. Each result shown in the
es is a mean value, calculated, as shown below, for a 95 %
idence interval (CI). This interval was calculated by means of
Student *t* distribution from the relationship (Wilson, 1952)

$$\mathrm{CI} = \pm \frac{k\,\sigma}{\sqrt{n}},$$

where n = number of measurements; σ = standard deviation of t measurements; k = coefficient for 95 $^0/_0$ confidence interval obtai by integration of the Student t distribution.

In calculating the mean or standard deviation, all values w utilized if their deviations divided by the average deviation (cluding the doubtful deviation) gave quotients less than 2.5 or more than one measurement showed a ratio greater than 2.5. single doubtful result was discarded if its quotient was greater th 2.5.

Evaluation of Indicators. A review of the literature yielded qu a list of indicators which have been used in EDTA titration calcium. A number of the most promising were selected for inve igation and comparison. A synthetic sea water approximating t composition of natural sea water was titrated with EDTA, using t different indicators for end point detection. Results of these titratio their precision as shown by the confidence intervals, and vario observations regarding end point detection are summarized Table I.

Murexide was the first metal indicator reported for use in ED titrations, and widespread usage of it has followed. This meth applied to the determination of calcium hardness in natural wate is now standard (APHA, 1955). The difficulty experienced in e

TABLE I. EVALUATION OF VARIOUS INDICATORS

Indicator	*Meq. Found**	*95 $^0/_0$ CI†*	*Remarks††*
Murexide	0.2025	0.0007	Diff; Fl
Murexide-Naphthol G	0.2043	0.0017	Diff; Fl.
Cal-Red	0.2125	0.0005	Sharp
Erio R	0.2120	0.0003	Sharp
Erio SE	0.2124	0.0009	Diff
Calcein	0.2095	0.0008	Diff; Fl
Calcein-Thymolphth.	0.2091	0.0007	Diff; Fl

* Synthetic sea water sample, 0.2136 meq. taken. Mean value of four to determinations.

† Assigned by the Student t distribution (Wilson, 1952).

†† Diff = Difficult end point; color change involves disappearance of a tint a complex shade; *e.g.*, the disappearance of salmon in a purple.

Fl = Fluorescence, which occurs if titrated in daylight or fluorescent light; point change is thereby obscured.

detection appears to contribute to low results, and use of othol Green B as a screening agent to facilitate detection of the point did not improve results.

io SE, used by Flashka, *et al.* (Barnard, *et al.*, 1956) was tried, difficulty was experienced in detecting the end point. Fluorce interfered in the end point detection, using Calcein, and thymolphthalein with Calcein did not give satisfactory results. the various indicators shown in Table I, Cal-Red and Erio R superior in ease of end point detection, precision and stability. were tested further.

ection of End Point Color for Cal-Red Indicator. Welcher (1958) pointed out that consistency in choice of end point color is ed in visual titrations with Cal-Red indicator inasmuch as is a range of colors within which a selection may be made. n titrating pure calcium solutions, a clear easily recognizable is obtained. However, when titrating sea water samples by ns of the method presented in this paper, the end point is more ult to detect because of the presence of magnesium hydroxide. color shift of the indicator is from lavender to ultramarine to each step requiring about 0.1 ml of titrant.

shown in Table II, the precision obtainable with the ultrane end point is not as great as that with the blue end point.

E II. SELECTION OF COLOR USED FOR END POINT WITH CAL-RED INDICATOR

Sample	*Meq. Ca Found**	*95 °/₀ CI* ±	°/₀ *Dev.*	*End Point Color*
	0.4998	0.0015	—0.04	Blue
37.5 mg Mg	0.4937	0.0033	—1.26	Lavender-Ultramarine
	0.4953	0.0280	—0.94	
	0.4966	0.0066	—0.68	
37.5 mg Mg	0.4985	0.0142	—0.30	Blue
	0.4999†	0.0035	—0.02	
	0.4995	0.0085	—0.10	
	0.4995	0.0100	—0.10	
	0.5001	0.0033	+0.02	
	0.5000	0.0033	0.00	
	0.5002	0.0074	+0.04	

Mean of four to six determinations, excepting †, which is mean of nine deter-
ions.

Moreover these results are low by about 1 $^{0}/_{0}$ whereas those titrat
to a blue are low by only about 0.07 $^{0}/_{0}$. To increase the accura
of the end point detection, comparison was made with a refere
solution containing magnesium hydroxide titrated to the blue e
point.

It was noted also that the indicator increased in stability w
magnesium hydroxide precipitate present. The end point color p
sisted for several hours, thus permitting comparison of the end po
color of samples with those used in standardization. Rapid deco
position of the indicator in highly alkaline solution, as has been
ported by Belcher, *et al.* (1958), was confirmed when pure calci
solutions were titrated.

Control of Alkalinity of the Solution. When magnesium is separat
from calcium by precipitating magnesium hydroxide, the soluti
is adjusted to pH12 and held there with a buffering agent such
diethylamine (Hildebrand and Reilley, 1957). It was thought th
magnesium could be quantitatively precipitated by adjusting t
pH of the solution to this value simply by adding sodium hydroxi
in sufficient volume and that dilution resulting upon titration wou
not change the pH materially. Such was found to be the case.
series of titrations performed with varying amounts of sodium hydro
ide present indicated that five ml per sample of sodium hydroxi
potassium cyanide solution, prepared as specified in the reage
section, appeared to be sufficient.

Prevention of Coprecipitation of Calcium with Magnesium Hydr
ide. To prevent loss of calcium through coprecipitation with ma
nesium hydroxide, Patton and Reeder (1956) proposed that all b
one milliliter of the titrant be added prior to addition of the p
cipitating agent. Usually a preliminary titration is necessary
ascertain the volume of titrant needed. In the case of sea wat
titrations, the amount of titrant required can be calculated fr
the Ca/Cl ratio.

This variation of procedure was tested on sea water with Cal-R
and Erio R indicators. As shown in Table III, excellent results
respect to precision and accuracy were obtained with Cal-R
With Erio R the precision was satisfactory, but a desirable accura
was lacking.

Bond and Tucker (1954) suggested that sucrose be added to fo
a weak calcium complex which is stable enough to prevent calci

TABLE III. Effect of Adding Titrant Prior to Control of pH

Indicator	*Meq. Taken**	*Meq. Found†*	*95 % CI ±*	*% Dev.*
Erio R	0.4544	0.4780	0.0006	+5.2
Cal-Red	0.4544	0.4555	0.0006	+0.2

uget Sound sea water sample taken; value calculated from chlorinity and Ca/Cl and Sr/Cl ratios.

Mean of four to six determinations.

cipitation with magnesium but weak enough for the calcium act with EDTA. Another suggestion by these authors involved ipitation of calcium carbonate before formation of magnesium oxide. The calcium in the calcium carbonate is still titratable EDTA but the magnesium in the precipitated hydroxide is Neither of these modifications of procedure yielded satisfactory lts when tried by us.

ompleteness of Titration of Strontium. From the formation con- t for the strontium EDTA complex, log K = 8.63 according to cher (1958), the strontium in sea water should be completely ated with EDTA. This has been verified experimentally. Ad- onal strontium in the amount of 0.0217 milliequivalents added a sample of Puget Sound sea water containing 0.1818 milli- ivalents of titratable metallic ions was titrated completely.

CALCIUM CONTENT OF OCEAN WATERS

hirty-six water samples from three ocean stations have been lyzed for calcium, using the procedure described in this paper. orinities were determined by Mr. Ralph W. Riley, chemist, anography Department, University of Washington. The method cribed by Knudsen was followed, except that fluorescein was d as the indicator as recommended by Miyake (1939). These orinity values were verified by us, using the regular Knudsen hod. Results of analyses for a single station are presented in le IV as being representative.

o obtain calcium values for these samples it was necessary to rect for strontium, since both strontium and calcium are titrated EDTA. The strontium content was calculated from the chlorinity he water sample and from the Sr/Cl ratio. Recent work by Chow

TABLE IV. Calcium Content of Sea Water taken on Brown Bear Cru
No. 179 at St. No. 26 (48°12′ N, 127°17′ W) on 9 November 1957

Depth (*m*)	*Temp.* (° C)	*Chlorinity* $(^0/_{00})$	*Meq. Ca/l*	*Ca/Cl*
0	13.28	17.927	19.57	0.02141
10	13.28	17.931	19.60	0.02144
20	12.96	17.925	19.58	0.02142
30	11.74	17.973	19.54	0.02132
50	7.46	18.069	19.63	0.02130
75	7.02	18.102	19.70	0.02134
100	6.70	18.215	19.84	0.02135
125	6.93	18.404	19.99	0.02129
143	6.83	18.583	20.18	0.02127
167	6.85	18.690	20.45	0.02143
182	6.84	18.706	20.43	0.02139
271	5.98	18.780	20.40	0.02128
448	4.90	18.873	20.52	0.02129
678	4.22	18.941	20.54	0.02123
918	3.61	19.007	20.71	0.02133
1267	2.99	19.071	20.68	0.02133
1559	2.44	19.100	20.81	0.02133
		Mean	=	0.02134
		Standard Deviation	=	±0.00006
		Av. $^0/_0$ Deviation	=	0.6

and Thompson (1955a) has indicated a Sr/Cl ratio (by weight)
0.00042. Work of Smales (1951), Odum (1951) and Bowen (19
is in agreement with the work of Thompson and Chow. This va
was used in calculating the calcium values listed in Table IV. T
mean Ca/Cl ratio (by weight) for the 35 samples analyzed is 0.021
with an average deviation of 0.6 $^0/_0$. The ratios for the various dept
were in excellent agreement with the mean. On the basis of prese
work, no special significance is attached to the fact that the t
three values were somewhat high, since the magnitudes are b
slightly greater than the standard deviation.

Selected Ca/Cl ratios found by previous investigators are sho
in Table V. The earlier ratios were originally corrected for a stro
tium content which was later shown to be too high. The ratios
corded in Table V have been recomputed for a Sr/Cl ratio of 0.000
after the method of Webb (1938).

mentioned previously, evidence indicates incomplete pre-
tation of strontium oxalate along with the calcium oxalate.
equently the ratios involving oxalate precipitation, methods 1
2 in Table V, could be too low because of over-correction for
tium. Carpenter's result with oxalate precipitation, however, is
ubject to this criticism because the strontium content of the
m oxalate precipitate was ascertained by flame photometric
ination and was corrected correspondingly. Carpenter's ratios,
on chromatographic separation of calcium followed by EDTA
ion, should also be independent of strontium. Likewise Chow
hompson's ratio from flame photometric estimation of calcium
ld be unaffected by strontium.

e Ca/Cl ratio as ascertained from the present work is in general
ment with the ratios given by previous investigators listed in
e V. It is intermediate between the values based on calcium
ate precipitation and the ratio of Chow and Thompson with the

E V. SELECTED VALUES FOR THE CALCIUM-CHLORINITY RATIO OF OCEAN WATER

Author	*Location**	*Anal. Method†*	*Ca/Cl††*
Dittmar (1884)	All Oceans (4)	1	0.02128
Thompson and Wright (1930)	Pacific (30)	1	0.02115
Kirk and Moberg (1933)	Pacific (17)	2	0.02135
Miyake (1939)	Pacific (18)	1	0.02120
Matida (1950)	Tokyo Bay (15)	1	0.02130
Chow and Thompson (1955b)	Pacific (16)	3	0.02189
Carpenter (1957a)	Atlantic (24)	4	0.02119
Carpenter (1957b)	Atlantic (1)	4	0.02122
Carpenter (1957b)	Atlantic (1)	1	0.02126
Robinson and Pate	Pacific (36)	5	0.02134

Number in parenthesis indicates number of samples analyzed.

Method 1: Precipitated as oxalate, weighed as CaO.
Method 2: Precipitated as oxalate, titrated with permanganate.
Method 3: Estimated with flame photometer.
Method 4: Strontium separated by ion exchange, calcium titrated with EDTA.
Method 5: Titrated with EDTA.

Ca/Cl ratio calculated on weight basis. As corrected by Lyman and Fleming
) for air bouyancy in weighing, for reference standard used in chlorinity, and
anges in atomic weights. Results have been corrected where required for a
ratio of 0.00042.

flame photometer. This close agreement with previous work is a ed evidence of the accuracy of this method as applied to sea wa analysis. The speed and simplicity of this method should encour its usuage for determination of calcium in sea water.

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ELATIONSHIP BETWEEN METABOLIC RATE AND BODY IN AN ELASMOBRANCH (*SQUALUS SUCKLEYI*) AND IN A TELEOST (*OPHIODON ELONGATUS*)[1]

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ABSTRACT

method using polyethylene tubing of various sizes and a flow of water commen-
e with the size of the specimen has been employed to determine the resting
bolic rates of large fish. With female dogfish, ranging in size from 0.1–9 kg,
out 13° C, there is a linear regression of log metabolic rate on log body weight
a slope calculated at 0.74. The metabolic rates of ling-cod, ranging in body
ht from about 0.2–20 kg, gave a slope of 0.78.

INTRODUCTION

rom values available to him in the literature, Zeuthen (1947)
able to plot metabolic rates against body size for fish up to a
ximum size of only a little more than a kilogram in weight. He
cluded: "As a whole, the experiments seem to indicate that the
rease in metabolic rate, which appears well established [with
reasing body size for small fish] . . . most probably continues
large fish] . . ., but the uncertainty of this finding is so high that
completely impossible to predict anything concerning the metab-
m of large fishes. Measurements in this field would be of the
atest interest." Reviewing the subject of respiration of fish ten
rs later, Fry (1957) was not able to include measurements beyond
one kilogram level.

ur interest in this problem arose from a concern with changes
issue respiration which presumably take place with an increase

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ity of Washington.

in body size. Since such changes are poorly understood in fish it was first necessary to establish whether or not there is a decl in standard metabolism with increase in body size. As noted bel modification of a simple technique which has been in use for m than 50 years has made it possible to obtain metabolic rates of la fish. Reported here are measurements of metabolic rates of *Squa suckleyi* (elasmobranch) weighing up to 9 kg and of *Ophiodon elo atus* (teleost) weighing up to 20 kg.

METHODS AND MATERIALS

Winterstein (1908) devised a constant flow system which bath the gills of a fish with water; by the Winkler method for dissolv oxygen he could measure the difference in oxygen saturation tween the incoming water and the outgoing water after it had pass over the gills, thus computing the rate of oxygen uptake. Ege a Krogh (1915) modified the method only slightly by having the flowing water bathe the entire fish before running out into a c lecting device; thus the rate of flow could be computed.

In the present experiments, a water flow proportional to the creased size of the fish was passed through a cylindrical bag polyethylene tubing of a length and size suitable for the subje The rate of flow was measured every half hour either with a ves and stop watch (dogfish experiments) or with a calibrated flo meter inserted on the up-stream side of the metabolism chamb (ling-cod experiments).

Polyethylene tubing, in the form called "lay-flat", is availa commercially in a variety of gauges and widths and in any leng desired. In these studies three sizes were used: 1) width 8 inc in the "lay-flat" condition, wall thickness 0.002 inch; 2) width inches, wall thickness 0.004 inch; 3) width 18 inches, wall thickn 0.006 inch. When inflated with water to a cylindrical shape, circumference of item 1 was 16 inches, the diameter about 5 inch Item 3, the largest we were able to use in the tanks available to provided a cylinder with a diameter of nearly 12 inches.

One end of the polyethylene, cut to a length somewhat grea than the subject, was gathered around a #14 1-hole soft rub stopper and fastened firmly with an adjustable stainless-steel ho clamp. This end was then tested for leaks, after which the cylin was filled with water, the whole unit being contained in a la

provided with an independent flow of sea water. The fish was
duced head first, after which the other end of the bag was
ered and clamped to a second stopper. The stream of water
ugh the bag was led out of the tank, and its outflow was fixed
enough to keep the bag inflated but not overdistended. With
much pressure the bag would rupture, with not enough pressure
ould collapse. Since the bag was transparent, the fish could see
ugh it and could be observed at any time. The fish did not
ggle once it was in the bag, but its insertion into the bag was
times accomplished only with some effort. The two dorsal
s of the dogfish were clipped off with bone forceps before the
was placed in the bag.

he measured flow of water, siphoned from a constant-level
rvoir, was adjusted so that a readily measured difference in
gen content of the water was produced by the metabolism of
fish. Experiments were continued in some cases up to 36 hours,
water samples taken at half-hour intervals. Polyethylene is
ciently impermeable to oxygen so that a steep gradient of dis-
ed oxygen between the inside and the outside of the bag could
ccomplished by artificial means without noticeable change in
oxygen content of the water flowing through the bag.

n work with the ling-cod it was noted that the temperature of the
ller quantity of water passing through the polyethylene respir-
n chamber was slightly lower than that of the much larger and
e slowly moving body of water in the tank. Table II shows some
hese temperature differences. We assume that the actual tem-
ture of the fish was close to a mean of the incoming and out-
g water in the bag and not to that in the tank itself. A mean
perature of about 12° C was the objective. The fish of Puget
nd normally live in sea water a few degrees colder than 12°,
this was the lowest temperature which could be achieved con-
ently during summer months with the sea water system at
lay Harbor. Observations employing the sea water system at
ttle were made at similar levels to permit direct comparisons
ween ling-cod and dogfish.

ogfish, obtained by trawling, lived for long periods in the sea
er system at the Friday Harbor Laboratories and were considered
be in normal condition. Usually they were held in the water
tem without feeding for a few days before use so that the di-
ive tract would be empty. After completion of the metabolic

studies, the animals were dissected to ascertain that the digesti tracts were actually empty.

The ling-cod proved much more difficult to obtain by trawlir Therefore the majority were taken by hook and line or by lor line, and some of the small ones were taken by beach seine. Fortu ately the mouth of the ling-cod is tough, but fish that were consider injured were discarded. The ling-cod fed voraciously in the labo atory and could be kept for long periods before use, some remaini in the aquaria on the Seattle campus for more than a month. Sin digestion in these animals is slow, they had to be starved for abo two weeks before a resting metabolic rate could be measured. one early experiment, when an unusually high value for the met bolic rate was obtained, it was found later by dissection that t fish had still been digesting a good-sized sole; ingestion must ha occurred at least ten days before the experiment.

The oxygen content of the water was determined by the unmo fied Winkler procedure, using a 300-ml stoppered bottle for sampli and a 50-ml titration aliquot.

RESULTS

Squalus suckleyi (Dogfish)

Female dogfish employed in these experiments weighed up 8.9 kg, the heaviest ones being pregnant; the largest nonpregna subject weighted 5.7 kg. No males were used.

The data for this species are presented in two ways: 1) Table sets forth the individual values of the metabolic rates of each fi to show the variability; 2) the data have been plotted in Fig. 1 a log-log graph to show the degree of conformity to a straight lir For ease in plotting, several individual values have been lump together (see Table I) to give a single point on the graph. Eq. Y aX^b describes this straight line; the value of b, the regression metabolic rate on body size, obtained from the numerical data l the method of least squares, proved to be 0.74 for *Squalus suckle*

Ophiodon elongatus (Ling-cod)

The measured values for the oxygen uptake of the ling-co studied in this work are presented in Table II. Each individu value is the mean of many measurements obtained from seri samples taken for long periods of time following preliminary o

LE I. THE RESTING METABOLIC RATES OF FEMALE DOGFISH, *Squalus suckleyi*, EMPERATURES VARYING FROM 12–14° C. EACH VALUE REPRESENTS THE MEAN OF SIX TO TEN DETERMINATIONS MADE AT HALF-HOUR INTERVALS

ht	*Mean Weight*†	*O_2 Consumption (ml/min)*	*Mean O_2 Consumption*†	*Body Weight (kg)*	*Mean Weight*†	*O_2 Consumption (ml/min)*	*Mean O_2 Consumption*†
2	0.102	0.18	0.18	1.867	1.87	1.22	1.22
				2.488		1.44	
1	0.641	0.40	0.40	2.915		1.60	
					2.70		1.52
8		0.67					
5		0.58		3.195		2.15	
	0.94		0.62	3.242		2.88	
				3.350		1.97	
1		0.58		3.426		1.11	
3		0.96			3.30		2.03
	1.05		0.77				
				3.994		2.75	
14		0.65		4.291		2.02	
26		0.97		4.700		2.35	
30		0.96		4.782		2.32	
	1.12		0.86	4.861		2.52	
				4.950		2.41	
13		0.80			4.60		2.60
29		0.71					
37		0.85		5.672§		3.38	
55		0.80		5.698		3.54	
83		0.71		5.929§		3.35	
	1.24		0.77		5.76		3.42*
33		0.98		7.043§	7.04	4.06	4.06
86		0.81					
	1.55		0.89	7.849§	7.85	3.69	3.69
11		1.24		8.970§	8.97	2.72	2.72
43		0.93					
59		1.05					
78		1.38					
78		1.28					
	1.75		1.17				

For fish of similar size.

Pregnant.

Values for pregnant and nonpregnant were lumped because they were so close ther as to make it inadvisable to try to plot them separately.

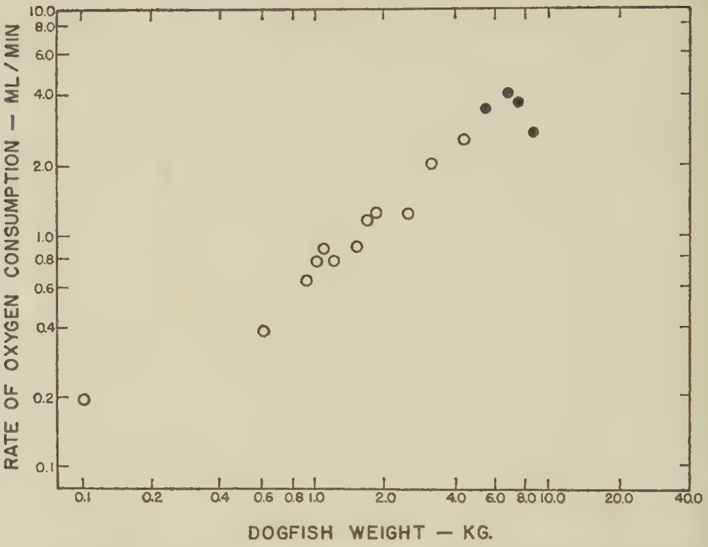

Figure 1. Log-log relationship of the rate of oxygen consumption with body weight female dogfish, *Squalus suckleyi*, at 13° C. Open circles, normal fish; solid circles, pregnant fi

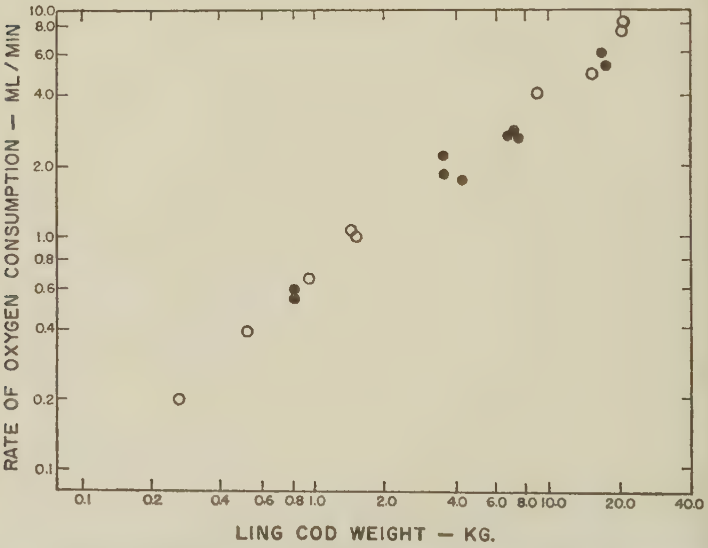

Figure 2. Log-log relationship of the rate of oxygen consumption with body weight ling-cod, *Ophiodon elongatus*, at 12° C. Open circles, normal fish; solid circles, sedated fis

E II. Standard Metabolism of Ling-Cod of varying Body Size. Each is the Mean of 10 to 20 Determinations made at Half-Hour Intervals. ucceeding Values for the Same Fish were made on Other Days

ght	*Temperature, °C*			*O_2 Consumption*	*Comments*
	Inflow	*Bath*	*Outflow*	*(ml/min)*	
	—	12.2	—	.20	—
	—	12.9–13.3	—	.38	—
	10.9	13.3	12.0	.57	Nembutal, 15 mg/kg
	10.8	13.1	11.6	.54	Nembutal, 15 mg/kg
	—	—	—	.64	—
	—	12.6	—	.97	—
	—	13.3	—	1.03	—
0	11.2	12.4	11.5	1.82	Nembutal, 15 mg/kg
	—	—	—	2.18	Nembutal, 15 mg/kg
0	10.9	13.0	11.2	1.69	Nembutal, 15 mg/kg
0	—	12.0	—	2.62	—
0	10.5	12.5	11.1	2.81	—
	10.6	11.3	11.0	2.86	Nembutal, 20 mg/kg
	10.3	10.9	11.8	2.64	Nembutal, 20 mg/kg
	10.9	12.1	11.4	2.52	Nembutal, 20 mg/kg
	11.1	12.3	11.6	2.56	Nembutal, 20 mg/kg
0	—	—	—	3.92	—
0	—	12.1	—	4.82	—
0	11.0	12.4	11.7	5.99	Nembutal, 12 mg/kg
	11.0	11.8	11.5	5.29	Nembutal, 12 mg/kg
0	—	12.2	—	7.96	—
	—	11.8	—	7.45	—

ation. It is well known that some species of fish require a long od of adjustment or conditioning after handling before they reach ate of minimum resting metabolism. Therefore the actual ex- ment was not begun until the preliminary serial samples showed consistency. Measuring the rate of the large specimens proved e only slightly more difficult than measuring that of the small s.

or this species, the value of b, the regression of metabolic rate body size, again obtained by the method of least squares, is , with a standard error of ± 6 $^0/_0$.

DISCUSSION

Whether or not a fish is at a minimal resting metabolic rate is not easy to determine. In the present case some additional evidence on this point was much needed. According to Geyer and Mann (1939), too small a chamber may excite certain fish. In our experiments the volumetric ratio of the largest bag to the largest fish used was about 4 to 1, whereas Geyer and Mann recommended a minimum ratio of 10 to 1. Furthermore, for purposes of comparison with *in vitro* tissue respiration rates, a minimum figure for the total rate of oxygen uptake by the postabsorptive but nonstarving fish was needed. We therefore made measurements of ling-cod which had been sedated with sodium pentobarbital (cf. Fry, 1957: 32). Comparison of data for sedated ling-cod and untreated individuals showed that all were at comparable levels of metabolic activity. Fig. 2 shows the average of all values for the oxygen consumption per minute of each fish plotted against body weight. The way in which the points fall on a straight line may be taken as evidence that the barbiturate was not depressing the metabolic rate. Also, we may judge from the agreement of data for the untreated and sedated fish and from the consistency of results for a single fish from day to day, that a minimum resting rate was being measured in the unsedated fish.

It is now possible to clarify in large measure the uncertainty expressed by Zeuthen (see Introduction). The decrease in metabolic rate with increasing body size is indeed well established for small fish. Fry (1957) has reviewed this point specifically for fish and has provided numerous references in addition to those given by Zeuthen. Directly to this point he cited ten other values (from less than 0.66 to 0.9 for different species of fish) for slopes relating the logarithm of the rate of metabolism to the logarithm of weight; most of these fish were small, usually below 200 g (.2 kg) for the largest body weight. Job (1955) obtained measurements of specimens of almost a kilogram in body weight. The good fit of his experimental data to a slope of 0.85 went far to remove any doubt that large fish would also show such a regression. Our value of 0.78 for ling-cod extends the generalization to 20 kg, and the method described seems to offer a relatively easy solution to the problem of measuring metabolic rates of much larger fish. The value of 0.74 obtained for

gfish is quite close to that for ling-cod, being both low or inter-
diate in comparison to the figures presented by Fry.

t is still impossible to forecast that measurements of other large
will be in agreement with the intermediate values reported here,
use significant correlations have not emerged from examination
he information accumulated so far. Temperature, salinity and
le of life seem not to play dominant roles, but the body of data
till small and a careful search may be well rewarded.

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THE EQUATIONS OF MASS CONTINUITY AND SALT CONTINUIT IN ESTUARIES[1]

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ABSTRACT

Equations of mass (or volume) continuity and salt continuity are developed f the two- and one-dimensional estuary from the basic forms of these equations three dimensions. The three cases of vertical, lateral, and sectional homogenei are treated. Some misuses of the continuity concepts as applied to estuaries ha appeared in recent literature. These are discussed. The effect of phase differen between tidal slack water and high tide on the nontidal drift in sectionally hom geneous estuaries is presented.

Introduction. Over the past ten years, occasional misuse of th continuity principles in estuaries has appeared in the literatur This has come about through attempts to simplify the proble under study by considering the estuary to be sectionally homogen eous, thereby reducing the problem to one spatial dimension. seems appropriate to develop rigorously the proper forms equations that express mass and salt continuity for estuaries unde the various assumptions regarding spatial variations of the pe tinent parameters.

The Basic Continuity Equations. Consider a right-handed c ordinate system x_i, with the x_1-axis directed longitudinally dow the estuary, the x_2-axis directed laterally across the estuary, an the x_3-axis directed vertically downward. The principle of conse vation of mass may be expressed as

$$\partial\varrho/\partial t = -\frac{\partial(\varrho v_i)}{\partial x_i},$$

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ere ϱ is the density and v_i the velocity at a given point x_i at a en instant of time t. If water is considered virtually incompressible, s relationship reduces to

$$\partial v_i \big/ \partial x_i = 0. \tag{2}$$

he principle of conservation of salt is expressed by

$$\partial s \big/ \partial t = -\frac{\partial}{\partial x_i}\left\{ s v_i \right\} + \delta \frac{\partial^2 s}{\partial x_i^2}, \tag{3}$$

re s is the salt concentration per unit volume at a point x_i and time t. The molecular diffusion of salt, $\delta\,(\partial^2 s/\partial x_i^2)$, is normally sidered negligible in the natural environment, and it is so con- ered here.

he instantaneous velocity, v_i, may be taken as equal to the sum a time mean velocity, $\bar{v}_i$, and of a velocity deviation v_i'. Like- se, the salt concentration, s, is expressed as the sum of a time an value $\bar{s}$ and of a deviation term s'. Thus

$$\begin{aligned} &\text{(a)} \quad v_i = \bar{v}_i + v_i' \\ &\text{(b)} \quad s = \bar{s} + s'. \end{aligned} \tag{4}$$

e period over which the mean is taken may be relatively short, that $\bar{v}_i$ and $\bar{s}$ are in themselves functions of time.

Substituting from (4) into (2) and (3) and taking the time mean these latter two equations over a period equal to or longer than period used in defining $\bar{v}_i$ and $\bar{s}$,

$$\partial \bar{v}_i \big/ \partial x_i = 0 \tag{5}$$

d

$$\partial \bar{s} \big/ \partial t = -\frac{\partial (\bar{v}_i \bar{s})}{\partial x_i} - \frac{\partial}{\partial x_i} < v_i' s' >. \tag{6}$$

Here the bracket < > represents a time mean, as does the super- ipt bar. The term $(\bar{v}_i \bar{s})$ represents an advective flux of salt while $v_i' s'>$ is a nonadvective or turbulent flux of salt. By analogy to molecular process, it is common in oceanography to replace the dy flux term $< v_1' s' >$ by the product of a diffusion coefficient d the spatial derivative of the mean salt concentration. In the st general case, oceans, estuaries, and other natural water bodies

must be considered as anisotropic. Hence, the nonadvective fl
of salt is expressed by

$$< v_i' s' > = -K_{ij} \partial \bar{s} / \partial x_j, \qquad ($$

where K_{ij} is the eddy diffusivity, and (6) becomes

$$\partial \bar{s} / \partial t = -\frac{\partial (\bar{v}_i \bar{s})}{\partial x_i} + \frac{\partial}{\partial x_i} \left\{ K_{ij} \frac{\partial \bar{s}}{\partial x_j} \right\}. \qquad ($$

It is generally assumed that eddy diffusion is only effective
the direction normal to the concentration gradient. Hence the la
term in (8) is too general. The required restriction on the diffusi
term can be imposed, while retaining the convenient tensor notatio
if it is required that

$$\begin{aligned} K_{ij} &= 0 \quad \text{for } i \neq j \\ \text{and} \qquad K_{ij} &\geqslant 0 \quad \text{for } i = j. \end{aligned} \qquad ($$

By use of (5), eq. (8) can also be written

$$\partial \bar{s} / \partial t = -\bar{v}_i \partial \bar{s} / \partial x_i - \frac{\partial}{\partial x_j} \left\{ K_{ij} \partial \bar{s} / \partial x_j \right\}. \qquad (1$$

In the remainder of the paper the superscript bar, indicating
time average, will be omitted. Hence the symbols v_i and s will re
resent time averages of velocity and salt concentration over
unspecified period of time.

The General Case of Three Spatial Dimensions. Eqs. (5) and (1
written out for the general three-dimensional estuary, are

$$\partial v_1 / \partial x_1 + \partial v_2 / \partial x_2 + \partial v_3 / \partial x_3 = 0; \qquad (1$$

$$\begin{aligned} \partial s / \partial t = -v_1 \frac{\partial s}{\partial x_1} - v_2 \frac{\partial s}{\partial x_2} - v_3 \frac{\partial s}{\partial x_3} + \frac{\partial}{\partial x_1} \left\{ K_1 \frac{\partial s}{\partial x_1} \right\} \\ + \frac{\partial}{\partial x_2} \left\{ K_2 \frac{\partial s}{\partial x_2} \right\} + \frac{\partial}{\partial x_3} \left\{ K_3 \frac{\partial s}{\partial x_3} \right\}, \end{aligned} \qquad (1$$

where, for convenience of notation, the double subscripts on K
K_{22} and K_{33} have been contracted to K_1, K_2 and K_3.

Eq. (12) applies not only to salt concentration but to the tin
rate of change in concentration of any conservative dissolve

erial, such as industrial pollution. It can also be applied to
oidal suspensions and those small particle suspensions with
ling velocities that are negligible compared to advection and
sion processes. In the case of nonconservative contaminants,
as nuclear materials or domestic wastes, additional terms rep-
nting decay rates would have to be added to (12).

he present possibilities of solving these general equations are
promising, particularly with the inclusion of complex boundary
itions of a real estuary. Numerical solution, using high speed
tronic computers, must await the development of machines with
h larger memory capacity than is now available. Also, some
pendent means of determining the diffusion coefficients is re-
ed. When computing machines of sufficient storage capacity
ome available, the general three-dimensional equation may be-
e useful in predicting the probable distribution in space and
e of a contaminant released into a given estuary. Such possi-
ties are being studied, but the procedures to be followed are
ond the scope of the present paper.

ost of the published work to date has dealt with the one- and
-dimensional approximations to the continuity equations, and it
n these approximations that misuse of basic concepts has resulted.

he Case of Two Spatial Dimensions. Some estuaries are nearly
ogeneous vertically, and spatial variations in velocity and salt
centration are limited to the two horizontal co-ordinates. Other
uaries exhibit little lateral variation, hence significant gradients
he fields of velocity and salt concentration exist only along the
gitudinal and vertical axes. In both of these situations the per-
ent equations may be reduced to two dimensions.

onsider the vertically homogeneous estuary first. The condition
o vertical variation in velocity and salinity will be delayed until
tain operations on basic equations have been completed in order
show clearly the significance of this assumption.

he origin of the co-ordinate system is assumed to be so located
t the plane $x_3 = 0$ coincides with mean tide level. The x_3 co-
inate of the surface at any time t is designated by $\eta(x_1, x_2, t)$.
x_3 co-ordinate of the bottom is taken as $h(x_1, x_2)$. Integration
(5) from surface to bottom gives

$$\int_{\eta}^{h} \frac{\partial v_1}{\partial x_1} \, dx_3 + \int_{\eta}^{h} \frac{\partial v_2}{\partial x_2} \, dx_3 + v_3(h) - v_3(\eta) = 0. \qquad (13)$$

Applying Leibnitz' rule, the first two terms of (13) become

$$\int_{\eta}^{h}\frac{\partial v_1}{\partial x_1}dx_3=\frac{\partial}{\partial x_1}\int_{\eta}^{h}v_1dx_3-v_1(h)\frac{\partial h}{\partial x_1}+v(\eta)\frac{\partial \eta}{\partial x_1}$$

and

$$\int_{\eta}^{h}\frac{\partial v_2}{\partial x_2}dx_3=\frac{\partial}{\partial x_2}\int_{\eta}^{h}v_2dx_3-v_2(h)\frac{\partial h}{\partial x_2}+v_2(\eta)\frac{\partial \eta}{\partial x_2}.$$

However, the condition that there can be no flow through boundaries gives

$$\text{(a)}\quad v_3(h)=v_1(h)\frac{\partial h}{\partial x_1}+v_2(h)\frac{\partial h}{\partial x_2}$$

and

$$\text{(b)}\quad v_3(\eta)=v_1(\eta)\frac{\partial \eta}{\partial x_1}+v_2(\eta)\frac{\partial \eta}{\partial x_2}+\frac{\partial \eta}{\partial t}.$$

Substituting (14), (15) and (16) into (13) gives, for the equati of continuity,

$$\frac{\partial}{\partial x_1}\int_{\eta}^{h}v_1dx_3+\frac{\partial}{\partial x_2}\int_{\eta}^{h}v_2dx_3-\frac{\partial \eta}{\partial t}=0.$$

Now, integrating (8) from surface to bottom and proceeding the same manner as above, we have for the salt balance

$$\frac{\partial}{\partial t}\int_{\eta}^{h}sdx_3=-\frac{\partial}{\partial x_1}\int_{\eta}^{h}v_1sdx_3-\frac{\partial}{\partial x_2}\int_{\eta}^{h}v_2sdx_3+\frac{\partial}{\partial x_1}\int_{\eta}^{h}\left\{K_1\frac{\partial s}{\partial x_1}\right\}dx_3$$
$$+\frac{\partial}{\partial x_2}\int_{\eta}^{h}\left\{K_2\frac{\partial s}{\partial x_2}\right\}dx_3.$$

The concept of vertical homogeneity implies that v_1, v_2, s, and K_2 are not functions of x_3. Hence (17) and (18) become

$$\frac{\partial}{\partial x_1}(hv_1)+\frac{\partial}{\partial x_2}(hv_2)+\partial h/\partial t=0$$

and

$$\frac{\partial(hs)}{\partial t}=-\frac{\partial}{\partial x_1}(hv_1s)-\frac{\partial}{\partial x_2}(hv_2s)+\frac{\partial}{\partial x_1}\left\{K_1h\frac{\partial s}{\partial x_1}\right\}$$
$$+\frac{\partial}{\partial x_2}\left\{K_2h\frac{\partial s}{\partial x_2}\right\},$$

where $h=h-\eta$.

ombining (19) and (20) gives

$$\frac{\partial s}{\partial t} = -hv_1 \frac{\partial s}{\partial x_1} - hv_2 \frac{\partial s}{\partial x_2} + \frac{\partial}{\partial x_1}\left\{K_1 h \frac{\partial s}{\partial x_1}\right\} + \frac{\partial}{\partial x_2}\left\{K_2 h \frac{\partial s}{\partial x_2}\right\}. \qquad (21)$$

quations similar to (20) and (21) have been applied to estuaries
h are not vertically homogeneous by using the mean values of
v_2, s, K_1 and K_2 over the vertical. Eq. (20) cannot be obtained
n (18) simply by taking mean values of various individual param-
s over the vertical, since the integrals on the right side of (18)
ive products of the parameters. An equation similar to (20)
d be used to describe the distribution in time and space of the
n salt content taken over the vertical, for an estuary which
ibits a vertical variation in salt content. However, the coefficients
and K_2 would not represent the mean value of the diffusion
fficients over the vertical, and, in fact, no physical meaning can
attached to these coefficients when the equation is employed in
h a case. The terms K_1 and K_2 merely become those functions
ich, when included in (20), allow that equation to describe prop-
y the distribution in time and space of the mean salt content.

or the case of a laterally homogeneous estuary, (5) and (8) are
egrated from the left-hand boundary, $a(x_1, x_3)$, to the right-
nd boundary, $b(x_1, x_3)$. By proper application of Leibnitz' rule
l by introducing the kinematic boundary condition, these equa-
ns become

$$\frac{\partial}{\partial x_1}\int_a^b v_1\,dx_2 + \frac{\partial}{\partial x_3}\int_a^b v_3\,dx_2 = 0 \qquad (22)$$

l

$$\int_a^b s\,dx_2 = -\frac{\partial}{\partial x_1}\int_a^b v_1 s\,dx_2 - \frac{\partial}{\partial x_3}\int_a^b v_3 s\,dx_2 + \frac{\partial}{\partial x_1}\int_a^b\left\{K_1 \frac{\partial s}{\partial x_1}\right\}dx_2 + \frac{\partial}{\partial x_3}\int_a^b\left\{K_3 \frac{\partial s}{\partial x_3}\right\}dx_2. \qquad (23)$$

he condition of lateral homogeneity reduces these equations to

$$\frac{\partial (wv_1)}{\partial x_1} + \frac{\partial (wv_3)}{\partial x_3} = 0 \qquad (24)$$

l

$$\frac{\partial (ws)}{\partial t} = -\frac{\partial (wv_1 s)}{\partial x_1} - \frac{\partial (wv_3 s)}{\partial x_3} + \frac{\partial}{\partial x_1}\left\{K_1 w \frac{\partial s}{\partial x_1}\right\} + \frac{\partial}{\partial x_3}\left\{K_3 w \frac{\partial s}{\partial x_3}\right\}, \quad (2$$

where $w = b - a$.

Combining (24) and (25) gives

$$w\frac{\partial s}{\partial t} = -wv_1\frac{\partial s}{\partial x_1} - wv_3\frac{\partial s}{\partial x_3} + \frac{\partial}{\partial x_1}\left\{K_1 w \frac{\partial s}{\partial x_1}\right\} + \frac{\partial}{\partial x_3}\left\{K_3 w \frac{\partial s}{\partial x_3}\right\}. \quad (2$$

Again note that this salt balance equation for a laterally hom geneous estuary cannot be applied to the mean salt concentrati across an estuary which is not laterally homogeneous without t loss of physical significance to functions K_1 and K_3.

The Case of One Spatial Dimension. Because of the complexi of the general three-dimensional equations, and even of the mo restricted two-dimensional equations given above, many investig tors have attempted to reduce kinematic and dynamic probler in estuaries to a single spatial dimension. It is in these treatmen that the most frequent misuse of continuity concepts has occurre

The appropriate equations for a one-dimensional estuary are o tained by integrating the equation of continuity, in the form giv in (5), and the salt balance equation, as expressed by (8), over cross-sectional surface area σ_1. This planar surface is taken perpe dicular to the x_1-axis and is bounded by the left and right sides the estuary, $a(x_1, x_3)$ and $b(x_1, x_3)$, by the surface $\eta(x_1, x_2, t)$, ar by the bottom $h(x_1, x_2)$. For eq. (5) the integration gives

$$\iint_{\sigma_1}\frac{\partial v_1}{\partial x_1}d\sigma_1 + \iint_{\sigma_1}\frac{\partial v_2}{\partial x_2}d\sigma_1 + \iint_{\sigma_1}\frac{\partial v_3}{\partial x_3}d\sigma_1 = 0. \quad (2$$

The two-dimensional analog of Leibnitz' rule for differentiati under the integral sign[2], when applied to the first term in (27), giv

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[2] I have been unable to locate, in any standard reference text available to n a statement of Leibnitz' rule for multiple integration when the limits of integrati are functions of the variable of differentiation. I have shown to my own satisfacti that the following form applies to the case under consideration: Given is $f(x_1, x_2, x_3,$ a continuous function within the bounded space of interest. Designate $\sigma(x_1, t)$ a planar surface perpendicular to the x_1-axis and varying with both x_1 and t. T function $F(x_1, t)$ is the integral of $f(x_1, x_2, x_3, t)$ over the area $\sigma(x_1, t)$.

$$F = \iint_{\sigma} f\,d\sigma.$$

$$\iint_{\sigma_1} \frac{\partial v_1}{\partial x_1} d\sigma_1 = \frac{\partial}{\partial x_1} \iint_{\sigma_1} v_1 d\sigma_1 - \frac{\partial \sigma_1}{\partial x_1} \oint v_1 dl. \tag{28}$$

The last two terms in (27) give

$$\iint_{\sigma_1} \frac{\partial v_2}{\partial x_2} dx_2 dx_3 = \oint v_2 dx_3 \tag{29}$$

$$\iint_{\sigma_1} \frac{\partial v_3}{\partial x_3} dx_2 dx_3 = \oint v_3 dx_2. \tag{30}$$

The time rate of change of the surface area can be expressed by

$$\frac{\partial \sigma_1}{\partial t} = \oint v_2 dx_3 + \oint v_3 dx_2 - \frac{\partial \sigma_1}{\partial x_1} \oint v_1 dl, \tag{31}$$

nce (27) becomes

$$\frac{\partial}{\partial x_1} \iint_{\sigma_1} v_1 d\sigma_1 + \frac{\partial \sigma_1}{\partial t} = 0. \tag{32}$$

Proceeding in the same manner with (8), integration of the salt lance equation over the surface area σ_1 reduces finally to

$$\frac{\partial}{\partial t} \iint_{\sigma_1} s d\sigma_1 = -\frac{\partial}{\partial x_1} \iint_{\sigma_1} v_1 s d\sigma_1 + \frac{\partial}{\partial x_1} \iint_{\sigma_1} \left\{ K_1 \frac{\partial s}{\partial x_1} \right\} d\sigma_1. \tag{33}$$

Now, if the estuary is sectionally homogeneous, so that v_1, s, and $\partial s / \partial x_1$ are not functions of x_2 and x_3, then (32) becomes

$$\frac{\partial}{\partial x_1} \left\{ \sigma_1 v_1 \right\} + \frac{\partial \sigma_1}{\partial t} = 0, \tag{34}$$

d (33) becomes

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e partial differential of F with respect to x_1 is given by

$$\frac{\partial F}{\partial x_1} = \frac{\partial}{\partial x_1} \iint_{\sigma} f d\sigma = \iint_{\sigma} \frac{\partial f}{\partial x_1} d\sigma + \frac{\partial \sigma}{\partial x_1} \oint v_1 dl,$$

ere $\oint dl$ represents the closed line integral around the boundary of the area, being taken along the boundary line.

$$\frac{\partial(\sigma_1 s)}{\partial t} = -\frac{\partial(\sigma_1 v_1 s)}{\partial x_1} + \frac{\partial}{\partial x_1}\left\{\sigma_1 K_1 \frac{\partial s}{\partial x_1}\right\}. \tag*{(3}$$

Combining (34) with (35) gives

$$\sigma_1 \frac{\partial s}{\partial t} = -\sigma_1 v_1 \frac{\partial s}{\partial x_1} + \frac{\partial}{\partial x_1}\left\{\sigma_1 K_1 \frac{\partial s}{\partial x_1}\right\}. \tag*{(3}$$

Consider a cross-section located in the river above the head of a estuary, where the rise and fall of the tide ceases. The integral velocity over the cross-sectional area at this location is simpl equal to the volume rate of flow of fresh water (instantaneous riv flow) designated as Q_f. If (32) is integrated from this upstrea cross-section to any position x_1 within the estuary, then

$$\iint_{\sigma_1} v_1 d\sigma_1 + \frac{\partial V}{\partial t} = Q_f, \tag*{(3'}$$

where V represents the volume of the estuary contained betwee position x_1 and the head of the tide. Then $\partial V/\partial t$ represents the rat of change of storage of water above the cross-section at x_1.

For a sectionally homogeneous estuary, (37) becomes

$$\left\{\sigma_1 v_1\right\} + \frac{\partial V}{\partial t} = Q_f. \tag*{(3}$$

In most estuaries the time rate of change in storage between th head of tide and any given cross-section is simply a harmonic ter of tidal period, hence the integral of (38) over a tidal cycle of perio T is given by

$$\int_0^T \left\{\sigma_1 v_1\right\} dt = \int_0^T Q_f dt = R, \tag*{(3}$$

where R represents the freshwater inflow per tidal cycle. In som estuaries the storage term may have a large variation over muc longer time periods than the tidal period (see, for instance, Todd an Lau, 1956). In such cases an added term representing this nor tidal variation in storage must be included in (39).

The equations developed here are based on the concepts of con tinuity of mass (which, for the nearly incompressible fluid, wate can be expressed in terms of volume continuity) and of continuit alt. Several investigators have developed and utilized inapplic- relationships through an erroneous assumption that the con- ty concepts apply to *fresh* water on the one hand and to *salt* r on the other. Thus Ketchum (1950), under the same assump- regarding upstream storage as those used here in arriving at defined the nontidal drift through any cross-section of the ary (designated as NTD) by the relationship

$$NTD = \frac{R}{F \times \bar{\sigma}_1},$$

$\bar{\sigma}_1$ as the mean cross-sectional area, R as given above in (39), F as the freshwater fraction. This latter term is given by

$$F = \frac{s_b - s}{s_b}, \tag{41}$$

re s_b is the salt concentration at the seaward end of the estuary s the salt concentration at the section in question.

ow, the non-tidal drift is simply the mean velocity, v_1, taken r the tidal cycle. Comparison of (39) with (40) shows that the er equation is inconsistent with properly applied continuity cepts in an estuary.

odd and Lau (1956), using essentially the same arguments as chum (1950), developed the following two relationships (in notation):

$$Q_f = F\sigma_1 v_1, \tag{42}$$

$$\int_0^T Q_f\,dt = \int_0^T F\sigma v_1\,dt = R. \tag{43}$$

omparison of (38) and (39) with (42) and (43) shows that these er equations cannot be correct, even when the time rate of nge of storage, $\partial V/\partial t$, is zero.

his particular erroneous application of continuity principles has n discussed more fully by Pritchard (1957), where it was shown t, for the simple case of constant river flow and constant tidal ge, the correct application of the continuity principles showed equations of Todd and Lau to be erroneous. Eqs. (38) and (39), ived at without these restrictive assumptions, verify the previous clusions for the more general case.

Return now to eq. (39). Note that both the cross-sectional a σ_1 and velocity v_1 are functions of time. Assume that both σ_1 a v_1 can be expressed as the sum of a mean value over the tidal peri plus a harmonic deviation term of tidal period; that is:

$$\sigma_1 = \bar{\sigma} + \sigma_U \qquad (4$$

and

$$v_1 = \bar{v}_1 + U, \qquad (4$$

where σ_U represents the change in cross-sectional area due to t rise and fall of the tide and where U is the purely oscillatory ti velocity. By substituting from (44) and (45), eq. (39) becomes

$$\overline{\sigma_1}\,\overline{v_1} + <\sigma_U U> = R', \qquad (4$$

where $<\sigma_U U>$ represents the time mean over the tidal period a $R' = R/T$ represents the mean river flow per unit time. Eq. (4 shows that the relationship between volume rate of inflow of fre water, R', and nontidal drift velocity, $\bar{v}_1$, depends on the amplitu and phase relationships of the harmonic variation in cross-sectio area and of the oscillatory tidal current. The term $<\sigma_U U>$ can quite large, exceeding the river flow in some cases by nearly order of magnitude.

If the tidal wave in an estuary is a pure standing wave, such th slack water occurs at high and low tide, then $<\sigma_U U> = 0$. Ho ever, if the wave is a pure progressive one, such that the maximu tidal velocity occurs at high and low water, then

$$<\sigma_U U> = -\tfrac{1}{2}\sigma_0 U_0, \qquad (4$$

where σ_0 is the amplitude of the harmonic variation in cross-sectio area and U_0 the amplitude of the variation in tidal velocity. this case, then, (46) becomes

$$R' = \overline{\sigma_1}\,\overline{v_1} - \tfrac{1}{2}\sigma_0 U_0. \qquad (4$$

The observed nontidal drift in sectionally homogeneous estu ries frequently exceeds the quotient of river flow over mean cros sectional area. Since the fraction of fresh water, F, in the expressi for nontidal drift, as developed by Ketchum and given here as e (40), is generally less than unity, these observations tend to supp conclusions of Ketchum. Eq. (48) shows that the observed drifts consistent with the correct application of continuity principles. sider, for example, some typical values for the parameters in . Let $U_0 = 1$ m/sec, $\overline{\sigma_1} = 10^4 \mathrm{m}^2$, $\overline{\sigma_0} = 0.2\,\overline{\sigma_1}$, and $R' = 10^2$ m³/sec.

$$\frac{\frac{1}{2}\sigma_0 U_0}{R'} = 10,$$

$$\overline{\sigma_1}\,\overline{v_1} = 11R'.$$

most estuaries, the phase relationship between tidal current tide height is intermediate between that for a pure progressive e and that for a pure standing wave. The resulting form of (46) ld be

$$R' = \overline{\sigma_1}\,\overline{v_1} - n\sigma_0 U_0, \tag{49}$$

re $0 \leqslant n \leqslant {}^1/_2$. Thus, in general, the nontidal drift velocity, $\bar{v}_1$, exceed the quotient of river flow over mean sectional area.

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A DAMPED KELVIN-WAVE OF GENERAL FORM

By

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1. *Abstract and Introduction.* This paper is concerned with a lo free progressive wave in a channel of uniform width and depth whe there is no component of current transverse to the channel. Th density of the water is supposed to be uniform and the rotation the earth and friction are taken into account.

Formulae for the case in which friction is neglected and the wav is harmonic in form were given in 1879 by Sir W. Thomson, afte wards Lord Kelvin. In 1929 I extended these formulae to the ca of a wave of general form without friction and in 1954 to the ca of a wave of harmonic form with friction.

In the present paper, the wave is taken to be of general form an the force of friction is supposed to be proportional to the curren but of limited magnitude. Since the wave is free, the tide-generati forces, wind, and variations of atmospheric pressure are not take into account.

2. *Notation and Fundamental Equations.* Denote by:

g the acceleration of gravity;

γ the geostrophic coefficient due to the rotation of the earth;

h the undisturbed depth of water, assumed uniform;

t the time;

x, y horizontal Cartesian co-ordinates, x being in the direction the channel and y transverse to this direction and to the le of x;

ζ the elevation of the water surface;

u the current, which is in the x direction;

k a coefficient of friction, assumed constant and uniform;

$F(t)$ the ratio ζ/h at the point $x = y = 0$;

and write

$$c = (gh)^{\frac{1}{2}}. \qquad ($$

The geostrophic coefficient γ is positive in the northern hem sphere and negative in the southern hemisphere.

The force of friction per area of bottom, when divided by the duct of density and the depth of water, is taken to be

$$2ku, \tag{2}$$

factor 2 being inserted for subsequent convenience.

The equation of continuity is

$$h\frac{\partial u}{\partial x}+\frac{\partial \zeta}{\partial t}=0 \tag{3}$$

the equations of motion are

$$\frac{\partial u}{\partial t}+2ku+g\frac{\partial \zeta}{\partial x}=0 \tag{4}$$

$$\gamma u+g\frac{\partial \zeta}{\partial y}=0. \tag{5}$$

elimination of u from (3), (4) and the use of (1) gives

$$\frac{\partial^2 \zeta}{\partial t^2}+2k\frac{\partial \zeta}{\partial t}-c^2\frac{\partial^2 \zeta}{\partial x^2}=0. \tag{6}$$

3. *Progressive Wave with Limited Friction.* It will now be assumed t the frictional coefficient k, which is inversely proportional to depth of water, is such that $k^2\zeta$ may be neglected compared h $\partial^2\zeta/\partial t^2$.

On multiplying (6) by the integrating factor $e^{kx/c}$ and neglecting ζ, the equation may be written in the form

$$\left(\frac{\partial}{\partial t}+c\frac{\partial}{\partial x}\right)\left(\frac{\partial}{\partial t}-c\frac{\partial}{\partial x}+2k\right)\left(e^{kx/c}\zeta\right)=0; \tag{7}$$

s differential equation is satisfied by

$$e^{kx/c}\zeta=hf\left(t-\frac{x}{c},\,y\right), \tag{8}$$

ere $f(,)$ is any numerical function of its two arguments.

From (8) it follows that

$$\frac{\zeta}{h}=e^{-kx/c}f\left(t-\frac{x}{c},\,y\right) \tag{9}$$

d then from (3) that

$$\frac{\partial u}{\partial x} = -e^{-kx/c}\frac{\partial f}{\partial t} = ce^{-kx/c}\frac{\partial f}{\partial x} \qquad (1$$

on omitting the arguments of f.

Integration of (10) with respect to x gives

$$\frac{u}{c} = e^{-kx/c}\left\{ f - k\int_{\alpha}^{t-x/c} f(\theta, y)\, d\theta \right\} \qquad (1$$

on neglecting

$$\frac{k^2}{c}\int_{\alpha}^{t-x/c} f(\theta, y)\, d\theta$$

compared with $\partial f/\partial x$. Here the neglected ratio is substantially t same as in (7), and the constant α is determined by the permane conditions.

Substitution from (9), (11) into (5) gives

$$\frac{\gamma}{c}\left\{ f - k\int_{\alpha}^{t-x/c} f(\theta, y)\, d\theta \right\} + \frac{\partial f}{\partial y} = 0, \qquad (1$$

and it is easily verified that an integral of this differential equation

$$f\left(t - \frac{x}{c}, y\right) = e^{-\gamma y/c}\left\{ F\left(t - \frac{x}{c}\right) + \frac{k\gamma y}{c}\int_{\alpha}^{t-x/c} F(\theta)\, d\theta \right\}, \qquad (1$$

whatever function $F(\,)$ may be, provided that

$$\frac{k^2\gamma y}{c}\int_{\eta=\alpha}^{t-x/c}\int_{\theta=\alpha}^{\eta} F(\theta)\, d\theta\, d\eta$$

may be neglected compared with $F(t - x/c)$. The ratio neglected i (13) is substantially the same as that neglected in (7), (11) mult plied by $\gamma y/c$.

From (9), (11), (13) it follows that

$$\frac{\zeta}{h} = e^{-kx/c - \gamma y/c}\left\{ F\left(t - \frac{x}{c}\right) + \frac{k\gamma y}{c}\int_{\alpha}^{t-x/c} F(\theta)\, d\theta \right\} \qquad (1$$

$$\frac{u}{c} = e^{-kx/c - \gamma y/c}\left\{ F\left(t - \frac{x}{c}\right) - k\left(1 - \frac{\gamma y}{c}\right)\int_{\alpha}^{t-x/c} F(\theta)\, d\theta \right\}; \qquad (1$$

these formulae give the surface elevation and current at any plac and time in terms of the function $F(\,)$. At the point $x = y = 0$, th formula (14) reduces to

$$\frac{\zeta}{h} = F(t)$$

onformity with § 2. The only restriction on the function $F(t)$ at it shall be physically interpretable. It is the generality of function $F(t)$ which makes the wave represented by (14), (15) of general form.

he formulae (14), (15) represent a wave progressing in the positive ction of x with speed of propagation c and with an amplitude h depends on position and on the geostrophic and frictional cients.

the direction of propagation, the variation of the amplitude iven by a frictional factor which decreases exponentially. In the ction transverse to that of propagation, the variation of the plitude depends on a geostrophic factor which, in the northern isphere, increases to the right, and on a term which contains h the geostrophic and frictional coefficients. This is the motion ch is called a damped Kelvin-wave of general form.

n the special case in which the wave is harmonic in time,

$$F(t) = A \cos \sigma t,$$

re A, σ are constants. Then

$$\int_{\alpha}^{t-x/c} F(\theta)\, d\theta = \frac{A}{\sigma}\left\{\sin \sigma \left(t - \frac{x}{c}\right) - \sin \sigma \alpha\right\},$$

, if there is no part of ζ or u independent of t, $\alpha = 0$. The form- e (14), (15) then reduce to

$$\frac{\zeta}{h} = A e^{-kx/c - \gamma y/c}\left\{\cos \sigma \left(t - \frac{x}{c}\right) + \frac{k\gamma y}{\sigma c}\sin \sigma\left(t - \frac{x}{c}\right)\right\}$$

$$\frac{u}{c} = A e^{-kx/c - \gamma y/c}\left\{\cos \sigma \left(t - \frac{x}{c}\right) - \frac{k}{\sigma}\left(1 - \frac{\gamma y}{c}\right)\sin \sigma\left(t - \frac{x}{c}\right)\right\}$$

the neglected ratio is k^2/σ^2.

aking $k = 0.002\, C/h$, where C is the maximum current (see udman, 1953: 310), the neglected ratio is $4 \times 10^{-6}\, C^2/\sigma^2 h^2$, and h $h = 100$ m, $C = 50$ cm/sec, $\sigma = 2\pi/12$ hr, the ratio is 0.0046.

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RTICULATE MATTER IN THE OXYGEN-MINIMUM LAYER[1]

By

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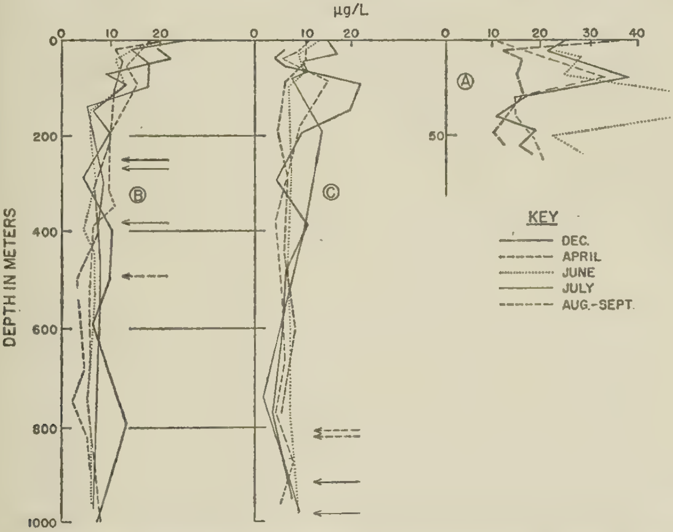
view of the interest in oxygen distribution in the ocean, it advisable to bring to light some observations which were in the 1930's but which were never published. Some of these



gure 1. Particulate nitrogen in micrograms per liter at Sts. A, B and C, during 1937– rrows indicate levels of oxygen minimum.

a were collected at the same time as those previously reported Rakestraw and Carritt (1948).

Vater samples were collected five times during 1937–38 from e key stations: St. A, on the Continental Shelf about 30 mi SE Montauk Point (Lat. 49°40′ N; Long. 71°45′ W); St. B, in the e water northwest of the current of the Gulf Stream (Lat. 00′ N; Long. 70°40′ W); St. C, in the Sargasso Sea southeast of

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the Gulf Stream (Lat. 35°30′ N; Long. 67°30′ W). Samples w taken during 1939 also at Sts. B and C.

Determinations of "particulate-nitrogen" were made by a meth previously described (von Brand, 1935). While these analyt results are in terms of micrograms of nitrogen in particulate mat contained in one liter of water, they afford at least a relative co parison of the content of total organic particulate matter in water. Results are shown in Figs. 1 and 2.

It is scarcely necessary to indulge here in a general discussion the origin of the oxygen-poor layer, since past and current vi on this question have been adequately summarized by Richa (1957). Many factors undoubtedly contribute to this phenomen including: vertical distribution and origin of oxidizable orga matter, relative rates of sinking and of oxidation, velocities horizontal and vertical advection, coefficients of eddy diffusi

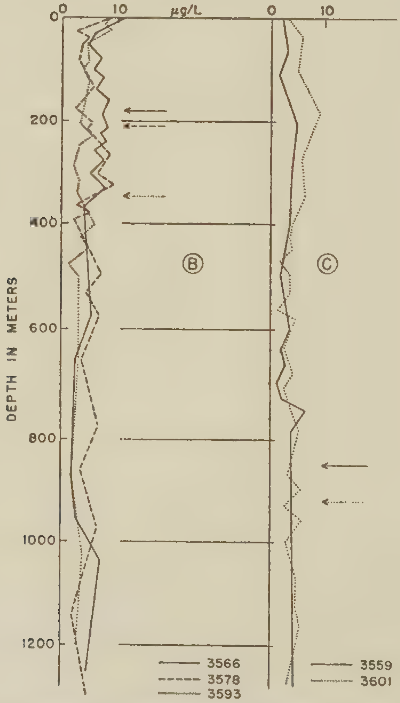

Figure 2. Particulate nitrogen in micrograms per liter at Sts. B and C, during 19 Arrows indicate levels of oxygen minimum. Numbers correspond to Atlantis stati

ation of rate of oxidation with temperature, pressure and oxy- concentration, etc. In fact, the very nature of the determinative ors will doubtless vary from place to place.

veral of the theoretical pictures which have been proposed vell, 1938; Wattenberg, 1939) postulate an accumulation of nic particulate matter at the level of greatest stability, near the om of the thermocline, and it has been supposed that this is ortant in determining the depth of the oxygen-minimum zone. vever, inspection of Figs. 1 and 2 shows no such relation. Ob- sly the vertical distribution of particulate matter is irregular although it seems to be more abundant near the surface, there ertainly no indication of any accumulation in the zone of low gen.

rlov (1953) has also determined the vertical distribution of iculate matter (organic plus inorganic) by an entirely different hod, and while his results occasionally show a higher concen- ion in the low-oxygen zone, there are as many cases in which reverse is true.

pparently we must abandon any conception that particulate tter accumulates in the oxygen-minimum zone.

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THE INFLUENCE OF THE CONTINENTAL SHELF ON THE TID OF THE ATLANTIC COAST OF THE UNITED STATES

By

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ABSTRACT

Examination is made of the hypothesis that the tide along the eastern coas the United States results from a co-oscillation of water over the Continental S engendered by motion at the continental slope, the barrier against which the oce tidal wave is reflected. Using methods which are effective in analyzing tides embayments, the range of tide and the time of high water over the contine slope have been estimated from data on the tide at the coast and from the topo phy of the off-lying shelf. Estimates indicate that the time of high water and mean range of tide along the continental slope are much more uniform than th at corresponding positions along the coastline, as consideration of the velocity waves in deep and shallow water demands. Estimated mean ranges along the 100 contour agree closely with those observed at oceanic islands in the Northwest Atl tic. The estimated velocities of tidal motion across the Shelf agree roughly with velocities of tidal currents measured from anchored vessels. It is concluded t the variation in local characteristics of the tide along this coast may be explai by the influence of the topography of the Continental Shelf upon tidal mot The general application of these results is discussed.

INTRODUCTION

Present knowledge of tidal movement in oceanic basins is bas almost exclusively on observations made along the coasts. It only at oceanic islands that the ocean tide has been observed affected by the disturbing influence of continental boundaries. Co sequently charts of cotidal lines of the oceans, such as those p pared by Whewell (1833), Harris (1904), Sterneck (1920) and D

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The author's interest in tidal phenomena began during a visit to Friday Har at Professor Thompson's invitation in 1948, and his first publication on the sub contains a consideration of the tides in that region. The present paper is con buted in grateful recognition of the stimulus received from Professor Thomp at that time.

h (1944), assume of necessity that the timing of the ocean tide
elated to the time of high water at the coast. It has been rec-
ized, of course, that shallow water distorts tidal behavior.
ewall wrote in 1836: "... the velocity of the tide-wave ... is
much less near the shore than it is in the open ocean: perhaps
may even consider the velocity of the tide-wave in littoral
ons as a quantity of a different order, and governed by different
from its velocity in the open ocean . . .". Since then the special
which relate the tide at the coast to the tide of the deep ocean
ot seem to have received the attention they deserve.

he influence of embayments on tidal behavior is well understood,
ast in situations of simple topography. In narrow embayments
tide may be considered to be a co-oscillation engendered by the
llation in the "outer sea". This co-oscillation approaches a
nding wave in form (Doodson and Warburg, 1941). The influence
eflection at the head of an embayment is such that it augments
amplitude of the tide to a degree which depends on the relation
he time required for the wave to traverse the length of the bay
the period of the wave. Amplification is maximal when this time
/$_4$ period. The effect of friction is to delay the time of high water
tive to that in the "outer sea" (Redfield, 1950). Fleming (1938),
o has employed these principles in examining the tides in the
lf of Panama, has extended his examination out to the continental
pe so as to draw some conclusions about the effect of the Shelf's
file on the velocities of the tidal currents developed.

n the present paper the hypothesis is presented that along the
tern coast of the United States the tide on the Continental Shelf
y be treated as a co-oscillation strictly analogous to that occur-
g in embayments. This co-oscillation is engendered by the ocean
e at the continental slope, which forms the effective barrier to
oceanic oscillation. The tidal wave on the Shelf is delayed in
ssing the shallow water and is augmented by reflection at the
st so as to produce the varied elevations and tidal intervals
erved along its length.

Vhen the profile of the continental margin is considered, it is
dent that the principal barrier to the oceanic oscillation must be
continental slope, since at this region the depth decreases
uptly from about 3,000 to 100 m. Tidal motion over the Conti-
tal Shelf must have negligible influence on the oceanic oscillation
ause of the relatively small volume of water involved. However,

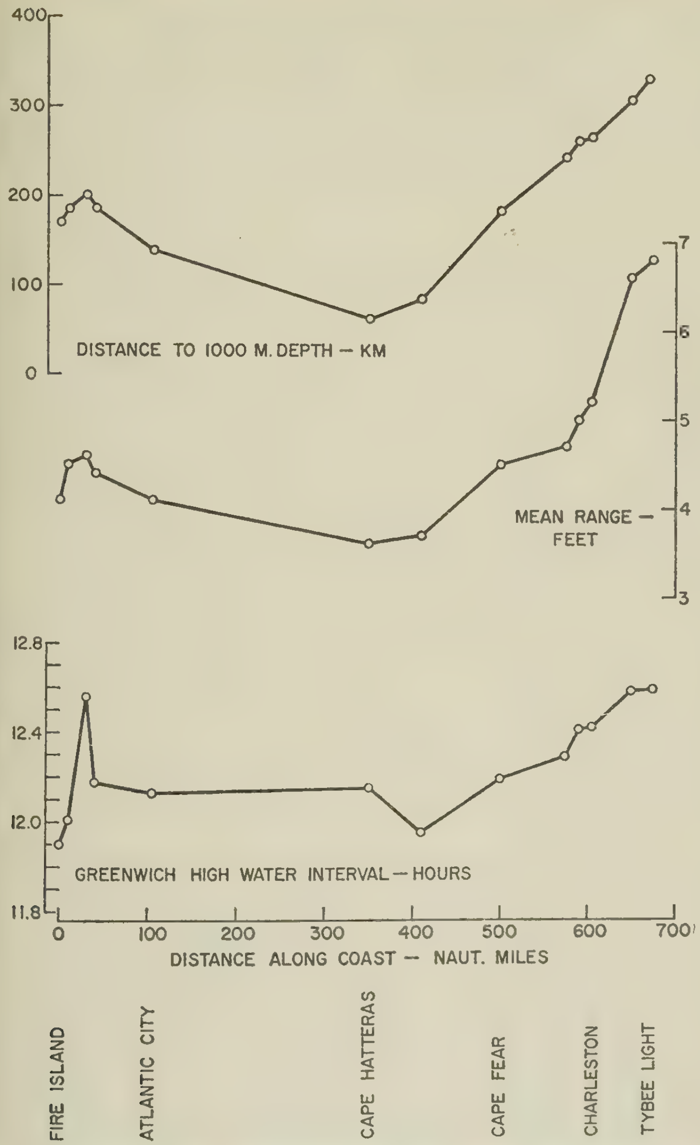
the ocean tide will give rise to a wave moving across the Con
nental Shelf which is reflected at the coast. The properties of t
tide observed at the coast are derived from the oceanic oscillati
after modification by the character of the co-oscillation across t
shallow water of the Shelf. See Fig. 1.

By analogy with tides in embayments, it may be expected th
the tide at the coast will be amplified by reflection to a degree i
creasing with the width of the Shelf up to the point where the tir
required for a wave to cross it equals $^1/_4$ period and that the tir
of high water will be delayed. If the oceanic wave front is near
parallel to the continental slope and if the shelf is of variable widt
it may be expected, because of the higher velocity of waves in de
water, that high water will occur more nearly simultaneously
the slope than along the shore. For the same reason, the gradien
in elevation should be smaller at the slope than along the coa

Cotidal charts of the Atlantic indicate that the eastern coast
the United States lies in a broad area in which the M_2 componer
which dominates the Atlantic tide, occurs at about 12 hours aft
the moon's transit at Greenwich. Harris (1900) proposed that t
semidiurnal tide along this coast was due to a standing oscillati
of ocean water across a nodal line extending northeastward fro
the Windward Islands. The American coast forms a barrier, almo
at right angles to the assumed direction of motion, against whi
this wave is reflected.

Along the coast the range of tide decreases progressively fro
nearly seven feet in Georgia to about half that value at Cape Ha
teras, north of which the tidal range increases to about four ar
one-half feet at New York. The time of high water varies in
parallel way. The width of the Continental Shelf between Georgia ar
New York varies in a manner similar to the tidal characteristic

Concepts which are effective in the analysis of tides in emba
ments have been used to deduce the properties of the tidal wa
across the Continental Shelf from data obtained at the coast ar
from the topography of the Shelf. The agreement of the times
high water estimated for positions along the continental slope ar
of the amplitudes at these positions and at oceanic islands provid
a criterion of the applicability of the procedures employed and
the validity of the hypothesis on which they are based. The ou
come explains the variation in tidal behavior observed along t
coast.



gure 1. Mean range of tide, Greenwich High Water Interval, and distance to 1,000 m our for selected outlying stations along the eastern coast of the United States.

Data. Data for the high water interval and mean range of ti recorded in Tide Tables Atlantic Ocean (U.S. Coast and Geode Survey, 1951) have been selected for 13 outlying positions. S Table I. The high water intervals for Cape Hatteras and Ca

TABLE I.

Station	*Lat. N*	*Long. W*	*Mean Range (feet)*	*Greenwich High Water Interval (hrs)*	*Distance fr Shore to 1,000 m Depth (km)*
Fire Island Breakwater	40°37′	73°18′	4.1	11.90	170
Long Beach	40°35′	73°39′	4.5	12.01	185
Sandy Hook	40°28′	74°01′	4.6	12.56	200
Sea Bright	40°22′	73°58′	4.4	12.18	185
Atlantic City	39°21′	74°25′	4.1	12.13	139
Cape Hatteras	35°14′	75°31′	3.6	12.15	62
Cape Lookout	34°37′	76°32′	3.7	11.95	85
Cape Fear	33°51′	77°58′	4.5	12.19	185
Cape Romain	33°01′	79°21′	4.7	12.29	245
Bull Bay, Jack Creek Entrance	32°56′	79°35′	5.0	12.41	263
Charleston Entrance, North Jetty	32°44′	79°48′	5.2	12.42	267
Hilton Head	32°14′	80°40′	6.6	12.58	310
Tybee Light, Savannah River	32°02′	80°51′	6.8	12.59	334

Lookout are revised figures supplied by the Coast and Geode Survey. Positions close to the mouths of larger bays have be eliminated because they appear to be influenced by tidal exchang with the bay, resulting in delayed high water intervals and, usuall in relatively small ranges. The data for Sandy Hook, which are i cluded, are suspect for this reason. East of Fire Island, New Yo the tides at outlying positions appear to be greatly modified by t tidal exchange with Long Island Sound and the Gulf of Mai while south of Svannah, Georgia the tidal ranges diminish progr sively, presumably as a result of tidal motion through the Stra of Florida.

Elevations are expressed as mean range of tide in feet, assum to equal approximately twice the amplitude of the M_2 compone nes are expressed in hours as the high water intervals relative to moon's transit at Greenwich.

or each of six positions between Fire Island Inlet and Tybee ht (Savannah, Ga.), the contour of the sea bottom was deter-ed along the shortest line to the 1,000 fathom contour, using . Coast and Geodetic Survey Charts 1000 and 1001.

stimation of the Mean Range of Tide at the Continental Slope.

is assumed that the tide on the Continental Shelf is a free co-illation driven by the ocean tide and reflected at the coast, the hod of Sterneck (1915) may be employed to estimate, by suc-ve application of approximate difference equations, the maxi-m elevation of the sea surface at increasing distances from the st. This method was used successfully by Sterneck and by De-t (1919) in analyzing the tides in a number of landlocked seas. procedure is described by Proudman (1953: 233). It is assumed his application of Sterneck's method that the motion is along the rtest path between the coastal point and the 1,000 m contour l is modified only by the distribution of depth along that path. e motion along such a path is thus considered to be like that in narrow gulf of unit width.

The method disregards friction, and it is implied in its application t components of motion at right angles to the path are negligible. e latter assumption cannot be justified rigorously since it is dent from the rotatory character of tidal currents observed at htships that such components of motion are present.

Application of the method enables one to estimate the ratio η/η_0 any distance from the coast and thus to obtain the maximum vation, η, at that distance if the elevation at the coast, η_0, is own. The 1,000 m contour is used to define the position of the tinental slope, and values of η found there are taken to indicate mean range of the oceanic tidal wave at the slope.

Sterneck's method was applied to determine the relative elevation, η_0, at successive intervals of 10 km from the shore. The result of calculation for Atlantic City is shown in Fig. 2. Note that over continental slope, or beyond, the maximum elevations change ry little with distance, which shows that the arbitrary depth of 00 m used to define the position of reflection of the oceanic wave ght be varied considerably without changing significantly the imate of the range of the oceanic tide. The maximum elevation at the 1,000 m contour is 0.66 that at the coast. Since the mea range at Atlantic City is 4.1 feet, the mean range at the 1,000 contour off Atlantic City is estimated to be 2.71 feet.

Table II shows results of similar calculations for the six select positions. The mean range at the 1,000 m contour is estimated increase from 2.71 feet at Fire Island to 3.36 feet at Cape Hatter and then to decrease to 2.79 feet at Tybee Light. This is an extrem difference of 0.65 feet as compared to 3.2 feet for the tidal rang along the coast. The measured mean range of tide in nearby ocean islands, Sable Island, Bermuda, Eleuthera, San Salvador, *et al.* given as 2.6 feet, which is close to the ranges estimated for the 1,000 contour off Atlantic City and Savannah.

The first criterion, that the oceanic oscillation has almost unifor elevations over great distances, is thus confirmed by the computatio Actually, the results show that the effect of the bottom topograph

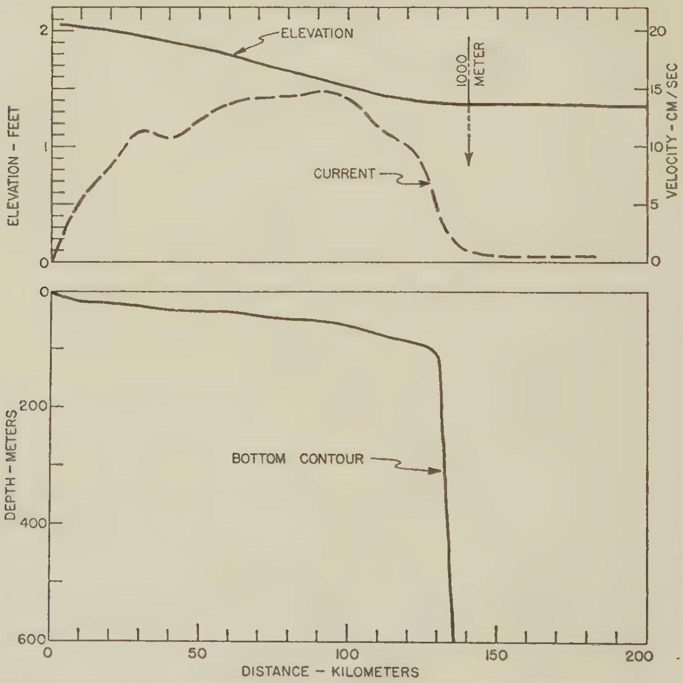


Figure 2. Profile of the Continental Shelf off Atlantic City and the distribution of estimat elevations at high water and maximum velocities of onshore and offshore tidal curren across this Shelf.

LE II. ESTIMATES OF THE MEAN RANGE OF TIDE AT THE 1,000 M CONTOUR

ation	*Bearing of Section-True*	*Mean Range at Coast (feet)*	*η/η_0 at 1,000 m Contour*	*Mean Range at 1,000 m Contour (feet)*
Island	133°	4.1	0.66	2.71
tic City	132°	4.1	0.66	2.71
Hatteras	112°	3.6	0.93	3.36
Lookout	120°	3.7	0.89	3.28
Romain	118°	4.7	0.64	3.00
Light	105°	6.8	0.41	2.79

ore than enough to account for differences in the tidal range at coast, since the greatest elevations of the oceanic tide are esti-ed to be off the capes of North Carolina, where the coastal range n fact least.

stimation of the Time of High Water at the Continental Slope. account for the differences in high water intervals along the coast the proposed hypothesis, it is necessary to introduce the assump- that the tidal wave is damped as it crosses the Continental lf. Otherwise high water would occur simultaneously, both along coast and at the continental slope.

or a wave undergoing reflection and damping in a channel of form width, it may be deduced that

$$\eta/\eta_0 = {}^1/_2\,(\cosh\ 2\mu x + \cos 2kx), \tag{1}$$

ere η/η_0 is the ratio of the elevation at high water at the position which η is measured relative to that at the barrier from which wave is reflected, kx is the phase difference due to the position which η is measured relative to the barrier, k is 360°, and μ is amping coefficient defined so that the attenuation per period is (Redfield, 1950). Using this relation, the phase difference be-en the tidal wave at the 1,000 m contour and the adjacent coast y be estimated for any chosen value of the damping coefficient μ m the values of η/η_0 obtained by the Sterneck method and given Table II.

nder similar conditions, the time of high water at any distance m the reflecting barrier is given by

$$\sigma t_H = \tan^{-1}\,(-\tan\ kx\ \tanh\ \mu x), \tag{2}$$

where σt_H is the time angle of high water at a point where t
phase difference is kx. Having obtained the value of kx at the 1,000
contour by eq. (1), the time of high water there relative to the ti
at the coast may be obtained, assuming the same value for t
damping coefficient, μ, in both steps of the calculation. For examp
at Atlantic City η/η_0 is found to be 0.66 at the 1,000 m conto
Assuming $\mu = 1.0$, kx is found to be $-50°$, using eq. (1). Applyi
this value of kx to eq. (2), σt_H is found to be $-9.2°$, or -0.32 hou
The Greenwich High Water Interval for the tide at Atlantic Ci
is 12.13 hours; consequently it is 11.81 hours at the continental slo

Lacking information on the damping coefficient to be applied o
the Continental Shelf, values characteristic of large embayme
have been employed. It has been found that a damping coefficie
of $\mu = 1.0$ satisfies the conditions in Long Island Sound and t
Bay of Fundy; 1.5 to 2.0 in the Straits of Juan de Fuca and Geor
(Redfield, 1950). Results of estimations using $\mu = 0.5, 1.0, 2.0$ a
presented in Table III.

Estimates obtained with $\mu = 0.5$ are the most satisfactory. T
extreme differences in Greenwich High Water Interval at the 1,000
contour are found to be 0.43 hours, or 0.22 hours if the early ti
at Fire Island Inlet is left out of account. This compares with
difference of 0.69 hours at the corresponding coastal positio
Moreover the trend is progressive, high water occurring earliest
the northeastern part of the slope, latest toward the southwe
Using $\mu = 1.0$, the spread of times is slightly less, 0.38 hours, b
high water is estimated to occur latest in the middle section of t
coast, which appears to be unreasonable. A damping coefficient
2.0 gives results which are quite unsatisfactory. The spread
values at 1,000 m is nearly as great as that at the coast, and hi

TABLE III. Estimates of Greenwich High Water Interval at the 1,00
Contour

Station	$\mu = 0.5$	$\mu = 1.0$	$\mu = 2.0$
Fire Island	11.75	11.58	11.14
Atlantic City	11.98	11.81	11.37
Cape Hatteras	12.13	12.10	12.04
Cape Lookout	11.95	11.87	11.77
Cape Romain	12.13	11.96	11.49
Tybee Light	12.18	11.69	—

er occurs distinctly later off the North Carolina capes than to north or south. No solution can be obtained for Tybee Light, the theory does not provide for such reduced values of η/η_0 re estimated by the Sterneck method.

though the assumption of the value of the damping coefficient ite arbitrary, it may be concluded that, by choosing a reasonvalue for this coefficient, the second criterion of the hypothesis be confirmed; namely, that the oceanic oscillation attains imum elevations almost simultaneously over great distances g the continental slope. The topography of the slope is consetly such as to account for the variation in both tidal range and of high water along the eastern coast of the United States.

otidal Lines of Continental Shelf. The mean range of tide and high water interval may be estimated for any point on the tinental Shelf by precisely the same procedure as that employed the 1,000 m contour. Such estimates were made for points where sections cross the 50, 100 and 400 m contours. The resulting ues, together with those for the 1,000 m contour and for the stal points of observation, have been combined in Figs. 3 and 4 rder to construct cotidal charts for mean range and time of h water on the Continental Shelf.

he approximate character of these charts is recognized. However, y serve to give a co-ordinated picture of the estimated results probably show in a general way the character of the tidal motion. ocean tide appears to approach the coast at right angles to the nd of the continental slope from a direction of 110°. South of e Hatteras, where the coast line falls away toward the west, crest of high water appears to cross the Shelf obliquely and benes progressively delayed in reaching the coast. The widening lf leads to substantial increase in tidal ranges along this part the coast.

idal Currents on the Continental Shelf. The hypothesis under mination considers that the tidal motion across the Shelf is tilinear and perpendicular to the 1,000 m contour. It thus ignores components of motion parallel to the coast. In contrast, obvations from lightships and other anchored vessels show that the l currents are rotary except near the entrances to the larger s (Haight, 1942). The current roses are so oriented, however, t at about three hours before high water, when maximal flow

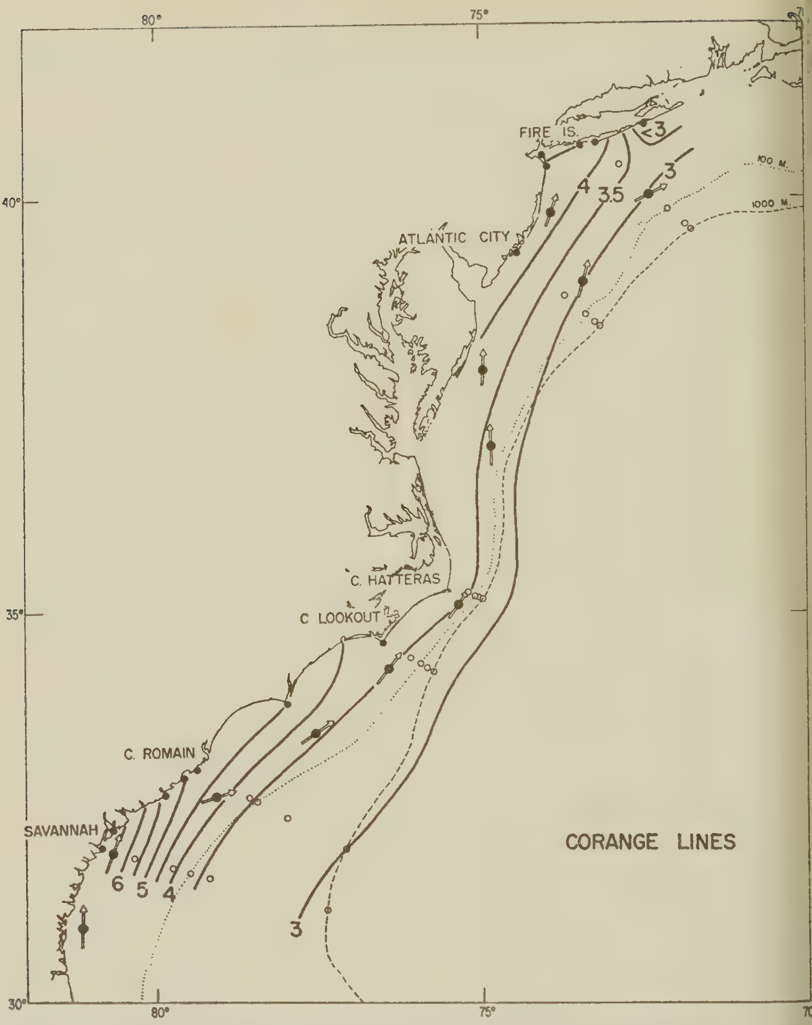
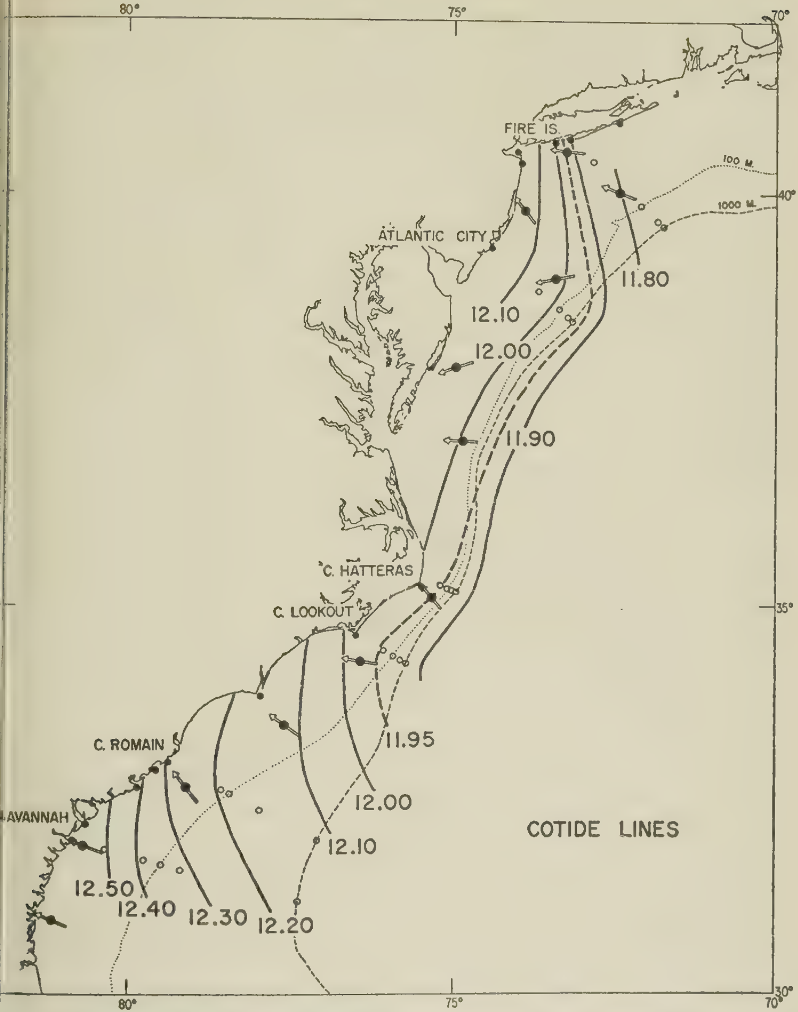

80°
75°
40°
35°
30°
FIRE IS.
<3
4
3.5
3
100 M.
1000 M.
ATLANTIC CITY
C. HATTERAS
C LOOKOUT
C. ROMAIN
SAVANNAH
CORANGE LINES
6
5
4
3

Figure 3. Estimated mean range of tide, in feet, on the Continental Shelf off the east
coast of the United States. Arrows show the direction of observed currents at high wat

onto the Shelf is expected, the direction of flow is approximate
normal to the coast. At high water, when the change in elevati
is zero, the currents flow northeasterly, parallel to the shore li

These relations are illustrated in Figs. 3 and 4, in which arro
indicate the direction of motion observed at anchored vessels.
Fig. 4 the direction of current when the shoreward component


80°
75°
70°
FIRE IS.
100 M.
1000 M.
40°
ATLANTIC CITY
12.10
11.80
12.00
11.90
C. HATTERAS
C. LOOKOUT
35°
C. ROMAIN
11.95
12.00
AVANNAH
COTIDE LINES
12.10
12.50
12.40
12.30
12.20
80°
75°
70°
30°

gure 4. Estimated time of high water, in hours after the moon's transit at Greenwich, he Continental Shelf of the United States, made on the assumption that the damping ficient, μ, is 0.5. Arrows show the direction of observed currents three hours before water.

v is maximal, approximately three hours before high water, is wn superimposed on the cotidal lines. In Fig. 3 the direction of v at high water is shown superimposed on contours indicating relative elevation of the sea surface at that time.

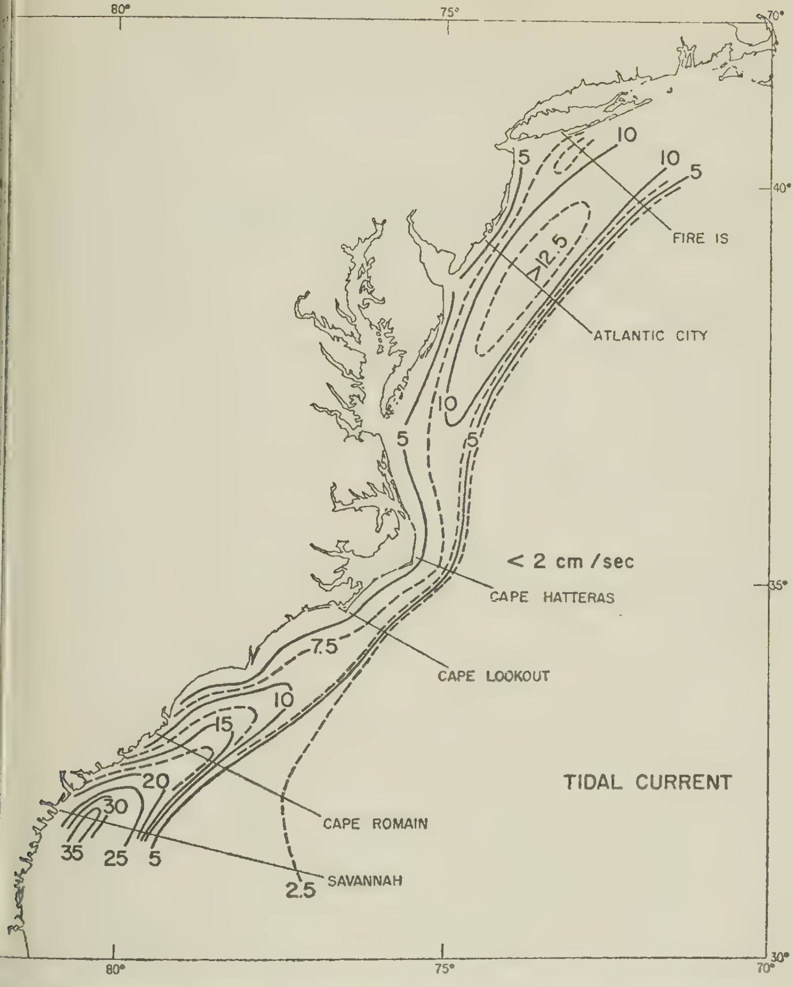
The assumption that components of motion parallel to the co may be ignored is justified to a certain extent by the fact that th components are small at the time of maximal flow on and off t Shelf and that they reach their maximum strength only at high a low water, when on- and off-shore flow is zero. Moreover, the chan in volume caused by such components flowing out of a section one side will be compensated by flow into the section from the oth

The latter assumption is not exact, however, because it is observ that the coastwise currents at the time of high and low water much stronger south of Cape Lookout than north of that poi Such a distribution of coastwise components may be expected augment the elevations on the coast at high water in the neighb hood of Cape Hatteras and Cape Lookout, in a degree not consider by the theory. Such augmentation in turn would lead to exaggerat estimates of the tidal range at the 1,000 m contour and thus m account for the higher values estimated for these positions.

The method employed to calculate elevations of the sea surfa across the Shelf yields also estimates of the maximum velocity flow associated with tidal motion. The distribution of velocity tained along the Atlantic City section is shown in Fig. 2. Usi similar data for the several sections, Fig. 5 has been prepared show the estimated maximum transverse velocities along the Sh between Fire Island and Savannah.

As shown in Fig. 5, beyond the 1,000 m contour the tidal vel ities are less than 2 cm/sec. The currents increase markedly about the 100 m contour and attain greatest velocities in m regions a short distance inside this contour. These relations similar to those estimated by Fleming (1938) for the Gulf of Panan The highest velocities occur off Savannah relatively near the co because of the local bottom topography. This section and that Cape Romain show also some influence of the relatively shoal wa over the Blake Plateau in accelerating the oceanic tidal moveme Between the 1,000 and 100 m contours the current increases fr 2.5 to 5 cm/sec as the Continental Shelf is approached.

The estimated velocities may be compared with direct measu ments of surface tidal currents made with current poles from chored vessels. See Table IV. The mean hourly velocities directions of such tidal currents, from which the nontidal current been eliminated, are given by Haight (1942). The maximum flo and ebb velocities have been averaged to give the values for m


80°
75°
70°
40°
35°
30°
10
10
5
5
FIRE IS
12.5
ATLANTIC CITY
10
5
5
< 2 cm /sec
CAPE HATTERAS
7.5
CAPE LOOKOUT
10
15
20
30
35
25
5
TIDAL CURRENT
CAPE ROMAIN
SAVANNAH
2.5

gure 5. Estimated maximum onshore and offshore tidal current, in centimeters per d, on the Continental Shelf off the eastern coast of the United States.

d currents listed in Table IV. No correction has been made for departure in direction from a path normal to the coast. Such ection would decrease the values up to 20 $^0/_0$. The estimated ents at the position of the vessels are taken from Fig. 5 and given to the nearest 2.5 cm/sec.

omparison of the measured currents with those estimated shows

general agreement in order of magnitude and in indicating mu
stronger currents off the coasts of Georgia and South Carolina th
to the northward. The estimates for Cape Lookout Shoals and Fry
Pan Shoals Lightship are substantially too high while those fr

TABLE IV. Onshore and Offshore Tidal Currents Measured from Ancho
Vessels (Haight, 1942: table 5) compared with Estimated Currents sho
in Fig. 5

Vessel	*Lat. N*	*Long. W*	*Date*	*Tidal Current (cm/*	
				Measured	*Estim*
Fire Island l.s.	40°28′	73°11′	1938–39	7.2	7.5
u.s.s. Cardinal	40°16′	73°15′	1919	5.9	7.5
u.s.s. Finch	40°04′	72°43′	1919	6.4	10.0
u.s.s. Falcon	39°04′	72°25′	1919	3.1	12.5
Winter Quarter Shoal l.s.	37°55′	74°56′	1912–13	5.0	10.0
			1918–20	3.6	
u.s.s. Brant	37°05′	74°51′	1919	9.3	10.0
Diamond Shoal l.s.	35°05′	75°19′	1921	1.8	7.5
Cape Lookout Shoals l.s.	34°20′	76°25′	1912	21.0	7.5
			1918–19	9.0	
Frying Pan Shoals l.s.	33°34′	77°48′	1912	23.5	10.0
			1918–21	16.0	
u.s.s. Long Island	32°42′	79°06′	1919	15.0	17.5
Charleston l.s.	32°41′	79°44′	1912	21.6	15.0
			1915–16	16.2	
			1921	15.7	
Martin's Industry l.s.	32°06′	80°28′	1912	26.7	25.0
			1916	22.9	
Savannah l.s.	31°57′	80°40′	1912	21.1	25.0
			1916	15.7	

positions north of Cape Hatteras are generally too low. Wh
measurements have been made at two or three different peri
at the same position, the agreement between successive periods
not better than that between the estimate and the nearest measu
ment. It seems probable that lack of agreement is due to ina
quacies in measurement quite as much as to faults in the estimatio
and it may be concluded that the estimated currents have so
validity, if not great precision, when applied to tides of the Con
nental Shelf.

DISCUSSION

e correlation between the tidal range on the Atlantic coast of
United States and the width of the Continental Shelf and the
onstration that variations in amplitude and time of high water
g the coast may be explained by the influence of the Shelf's
guration suggest that similar relations may exist more widely.
xamination of the amplitude of the M_2 component along the
ts of the world oceans, shown for example by Dietrich (1944:
3), indicates that semidiurnal tides of exceptional amplitude
in areas with unusually broad continental shelves. Examples
he southeast coast of South America and the northwest coasts
urope and Australia. Conversely, long stretches of coasts having
ively narrow shelves have semidiurnal tides of small amplitude.
mples are the west coasts of Africa and South America and the
coast of Asia. However, when the amplitude of the M_2 compo-
t at a large number of coastal positions throughout the world is
pared with the width of the off-lying continental coast, say, to
1,000 m contour, no satisfactory correlation is obtained. The
test amplitude of the M_2 tide occurring at any width of shelf
s increase with the width at a rate of about one foot per 20
tical miles. However, at any one width, amplitudes of any value
than the maximum may occur. It is only when the width of the
f is greater than 150 nautical miles that the smaller amplitudes
not to be found. It is evident that factors other than the width
he shelf influence the amplitude of the tide at the coast.

mong such factors may be listed: the amplitude of the ocean
itself; the angle of approach of the oceanic wave; the actual
file of the bottom across the shelf, which may be relatively deep
hallow within the limits on the shelf; the influence of local em-
ments in the coast line; and the period of the tidal component
question. Understanding of the relation of the tide, as observed
ng the coast, to the oscillation of the off-lying deep water conse-
ntly requires a detailed examination of these factors as they
ly to any region in question. The coast under consideration in
present paper is particularly favorable for such studies because
ocean tide occurs so nearly simultaneously along its length that
l movement on the Shelf may be dealt with as a transverse
llation. The system of motion in other regions is no doubt much

more complicated, but it is hoped that the application of princip similar to those employed in the present case may be effective clarifying the relation of the coastal tide to that of the ocean basi

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SOLVED SILICATE AND RELATED PROPERTIES OF SOME ESTERN NORTH ATLANTIC AND CARIBBEAN WATERS[1]

By

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Woods Hole Oceanographic Institution

> "*As marine plants are the ultimate source of food for much of the animal life in the sea, the role played by silicon is of fundamental importance*".
>
> T. G. Thompson and R. J. Robinson, 1932

ABSTRACT

ssolved silicate, phosphate, nitrate, and oxygen as well as salinity and temper-
were observed in several regions around the Antilles Arc and in the Woods
-Bermuda area. It is shown that silicate is generally in low concentration in
ce waters, where its ratio to phosphate, nitrate and oxygen consumption is
ble. At intermediate depths, silicate, phosphate and nitrate regeneration and
en consumption (AOU) proceed in the ratios, by atoms, of Δ AOU: Δ Si:
: Δ P = 270:16:16:1. In some of the water masses, silicate, nitrate and phos-
e occur in these same ratios but are in excess of the amount of regeneration
cted from the amount of oxygen consumption. However, silicate is clearly
linearly related to biological processes. In other water masses, notably in deep
r of the North Atlantic, the Puerto Rico Trench and the eastern Caribbean
and in anaerobic water of the Cariaco Trench, there are higher concentrations
licate than would be expected from the amounts of phosphate present. These
originate from *in situ* re-solution of skeletal remains of diatoms or from re-
ion of bottom deposits followed by upward diffusion.

ntroduction. The wide variability of silicate in the ocean should
e it a valuable characteristic for tracing water masses, and its
ogical involvement in the sea is of special interest. Although
ate is used in relatively large quantities by only a few groups of
anisms, principally diatoms, these occur in large numbers and are
ortant primary producers of organic matter. This special rela-
ship between silicate, the diatoms, and organic production sets
on apart from nitrogen and phosphorus, which are used by all
anisms. Some of the silicate which diatoms fix concurrently with

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Contribution No. 990 from the Woods Hole Oceanographic Institution.

their organic matter is redissolved in the water column upon th death and thus re-enters the ecological cycle. The balance eventua becomes incorporated in bottom sediments, there to become a p of the geological record and to represent a phase in the geochemi migration of silicon. This paper relates the distribution of silica in several oceanic areas to the biological cycle through nitrog phosphorus and dissolved oxygen and to hydrography through distribution and temperature-salinity correlations.

Studies of seasonal variations in silicate have demonstrated close relationship between diatom growth and depletion of silica from the water, and conversely, between regeneration of silicate a a decrease in the diatom population (Rabin, 1905a, b, 1910, 191 Brandt, 1920; Atkins, 1923a, b, 1926a, b, 1928, 1930; Thomps and Johnson, 1930; *et al.*). Studies of silicate and its distributi have been made by Clowes (1938), by Graham and Moberg (194 and by others. The data of Atkins (1928, 1953, *inter alia*), Coop (1933, *et seq.*), and others of the laboratory of the Marine Biologi Association at Plymouth, England, show seasonal variations silicate and phosphate which are more or less parallel; Coope paper on factors affecting the distribution of silicate shows (195 fig. 1) an approximately linear relationship between phosphate a silicate between about 25 and 600 m at a station in the Bay of Bisca

It has been stated that silicate in the ocean increases contin ously with depth (Sverdrup, *et al.*, 1942; Graham and Moberg, 194 but some of the Discovery data (Discovery Committee, 194 Sts. 1162–1184) show silicate maxima at slightly less than 1000 in the equatorial and South Atlantic. This type of vertical dist bution was the rule in a series of stations occupied by Atlantis the equatorial Atlantic in 1952. The maxima were clearly associat with the phosphate maxima and oxygen minima. These observatio made it clear that some features of the silicate distribution result from closely correlated biological phenomena.

Observations. Silicate was determined in samples from the easte Venezuelan Basin and the Cariaco Trench in the Caribbean Se the Atlantic region east of the Windward Islands from Tobago Martinique; the Puerto Rico Trench-Anegada Passage regi (Table I); and the area between Woods Hole and Bermuda. O servations between Woods Hole and Bermuda were made on r Bear Cruise 185, May 12 to 16, 1958 and r/v Crawford Cruise

TABLE I. STATIONS IN THE ANTILLES ARC REGION

ate	*Station Number*	*North Lat.*	*West Long.*	*Bottom Depth (m)*	*Depths at which eq. (1) is Satisfied*
EZUELAN BASIN					
5					
2. II	5272	13°30′	65°24′	3860	Phosphates not available
4. II	5273	14 14	63 25	1464	Phosphates not available
6. III	5282	13 09	62 15	2885	192–482; 867
7. III	5283	14 13	62 55	1483 ?	195–781
9. III	5284	16 03	66 02	4301	267–806
ADA-JUNGFERN PASSAGES					
2. III	5285	17°54′	65°51.5′	1955	188–1038; 1623–1818 (d.s.)
5. III	5286	17 53	65 20	3820	266–1030; 1850–3440 (d.s.)
5. III	5287	17 54.5	64 16	1975	279–854
RTO RICO TRENCH REGION					
7. III	5288	18°52′	63°05′	5880	455–2898
9. III	5289	19 56	62 50	6050	406–1461
1. III	5290	19 54	64 32	7260	385–2395
22. III	5291	19 52	66 35	7690	352–1964
T OF THE WINDWARDS					
19. II	5274	14°80′	60°42′	1089	140–488
21. II	5275	13 54	59 47	717	147–495
22. II	5276	13 25	58 19	2880	197–2750 (d.s.)
23. II	5277	13 50	56 53	4812	189–2387
24. II	5278	12 36	58 34	1851	195–1744 (d.s.)
26. II	5279	12 41	59 40	1020	181–561
IACO TRENCH REGION					
1957					
1. XI	5596	10°52′	66°00′	185	54–161
1. XI	5597	10 06	66 05	260	200–230 (not in Trench)
2. XI	5597 A	10 48	65 52	252	150–245
2. XI	5598	10 44	65 54	412	200
4. XI	5599	10 19	65 32	58	none
4. XI	5600	10 28	65 43	554	200 only
4. XI	5601	10 37	65 32	722	none sampled
5. XI	5602	10 52	65 33	845	197, 342
6. XI	5603	11 15	65 07	784	174–498 (not in Trench)
6. XI	5604	10 54	65 08	58	none
6. XI	5605	10 38	65 08	933	228 only
8. XI	5606	10 32	64 40	1343	186 only
8. XI	5607	10 32	64 41	1337	196 only

= deepest sample.

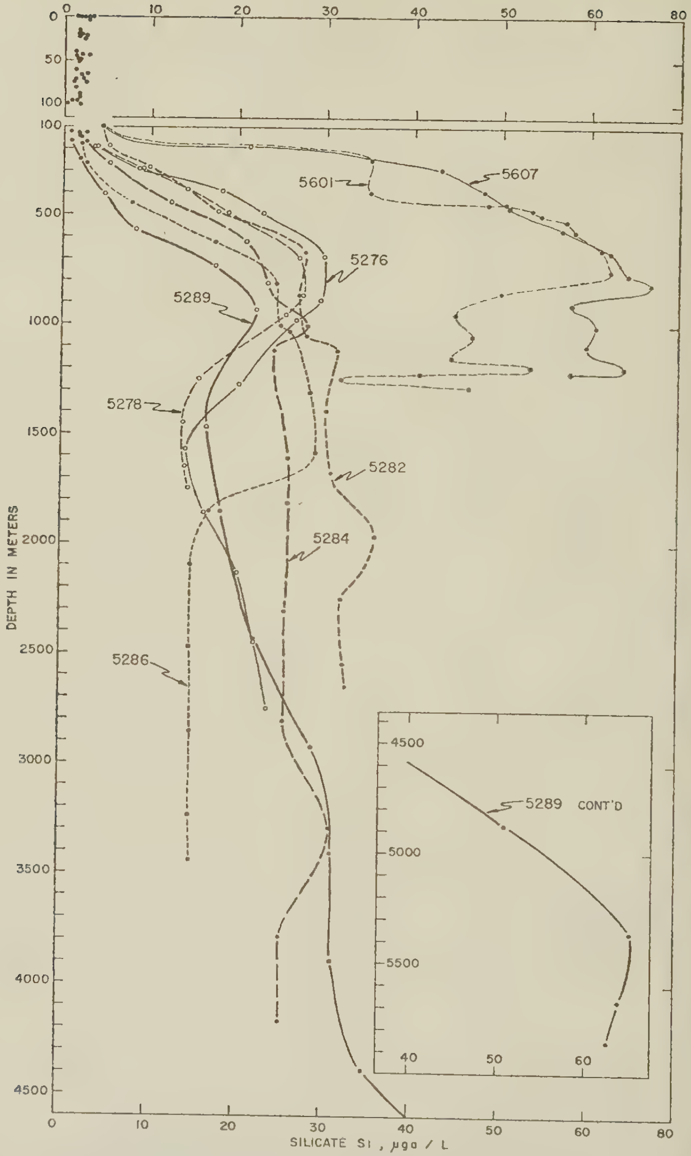


Figure 1. Silicate concentrations *vs* depth at representative stations in the Antilles A
region. Sts. 5601 and 5607 in the Cariaco Trench; 5282 and 5284, Venezuelan Basin; 527
5278, Atlantic Ocean east of the Windwards; 5289, Puerto Rico Trench; 5286, Anegad
Jungfern Passage region. Open circles correspond to those in Figs. 3 and 4.

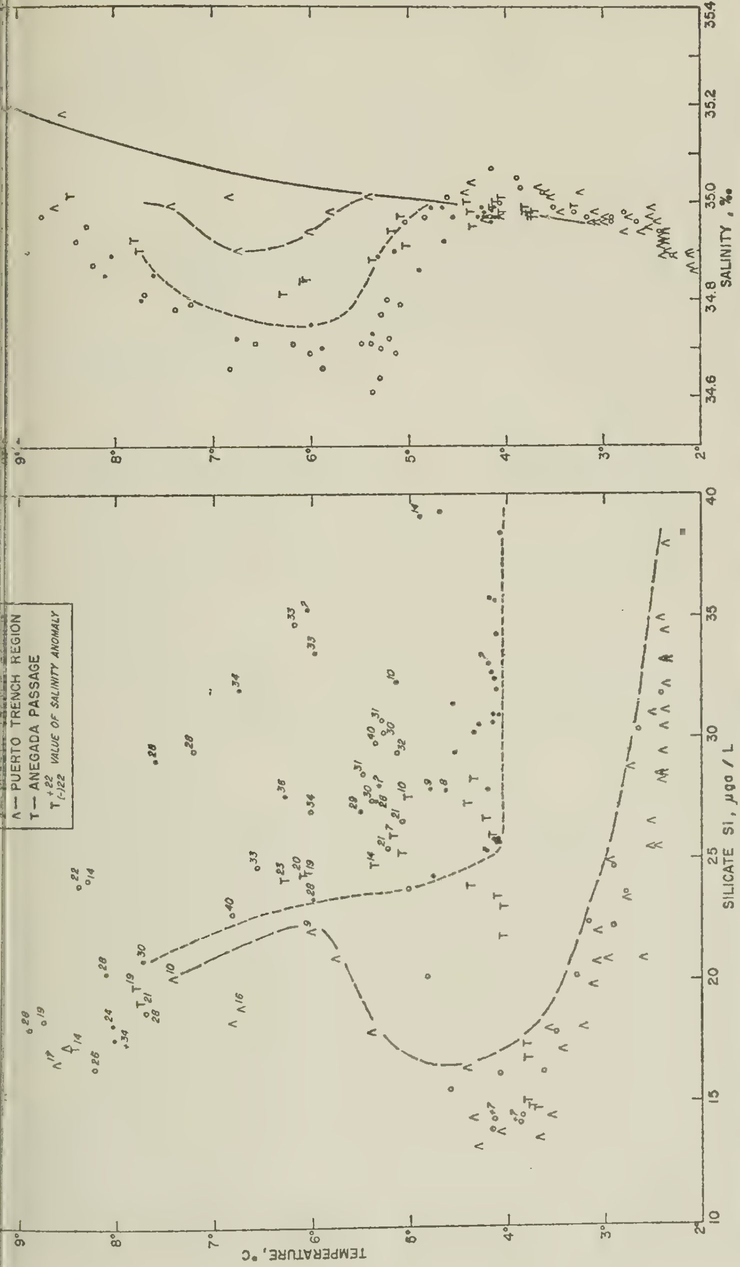


Figure 2. Temperature-silicate and temperature-salinity correlations. The solid curve is Iselin's (1936) correlation for western Sargasso Sea waters. Numbers on the temperature-silicate diagram are salinity anomalies and are negative unless otherwise indicated. Points having no numbers have salinity anomalies less than ± 5. Question marks indicate no salinity values are available. The short dashes envelope the samples from the Venezuelan Basin on the T/Si diagram, and those from the Puerto Rico Trench and from east of the Windwards on the T/S diagram. The long dashes envelope the samples from the Puerto Rico Trench on both diagrams. All samples from between Woods Hole and Bermuda having more than 20 μg-at silicate-Si/l (CRAWFORD Cruise 19) come from depths greater than 2500 m.

July 7 to 19, 1958; locations of the stations on these two cruis
are shown by Ketchum, *et al.* (1958: fig. 1). Temperature, salinit
dissolved oxygen, inorganic phosphate, total phosphorus, and silica
were observed. Nitrate data are also available for the Woods Hol
Bermuda samples, and sulfides were determined for the Caria
Trench samples.

Analytical Methods. Impetus has recently been given to the stu
of silicates by the introduction of the new sensitive and reproducib
analytical methods of Armstrong (1951) and Mullin and Riley (195
Samples from the Antilles Arc regions were analyzed by Armstrong
method directly after collection; color comparisons were made wi
the photoelectric colorimeter described by Ford (1950), using a r
(Corning No. 2404) filter.

The remaining samples, including those from the Cariaco Trenc
were analyzed using Armstrong's system of internal standards co
bined with Mullin and Riley's reagents and procedures; a Beckm
Model DU Spectrophotometer was used for color comparison
these determinations (one cm cells, 812 mμ). These samples, i
mediately frozen in polyethylene bottles, were so kept until abo
12 hours prior to analysis, when they were thawed and allowed
come to room temperature. Experience in this laboratory has show
this to be a satisfactory procedure for phosphates, nitrates, and n
trites (Ketchum, *et al.*, 1958) as well as for silicates.

Depth Distribution. Plots of silicate against depth at representati
stations in the area studied (Fig. 1) often show distinct silicate ma
ima at intermediate depths (800 to 1200 m), decreases at great
depths to secondary minima (1400 to 1800 m), and increasing co
centrations with depth below 1800 m. Exceptions to this rule a
found in the Venezuelan Basin, where the high concentrations o
served at 800 to 1200 m are maintained into water of greater dept
than 1200 m. The silicate concentrations in the Cariaco Trenc
(Sts. 5601, 5607) are much higher than those at other locatio
sampled, but maxima occur at about 800 m. The high silicate co
centrations observed in the Venezuelan Basin between 1100 a
2600 m are in striking contrast to concentrations in waters of simil
depth in western North Atlantic water masses. The difference
obvious on both depth-silicate and temperature-silicate diagra
(Fig. 2), may prove useful in indicating the isolation of the deep
Caribbean water.

ydrography. In the region of the Antilles Arc, the Atlantic cur-
s generally flow westward and northwestward. In the northern
t of the region (represented by the Puerto Rico Trench stations,
2), the “salt half” of the North Equatorial Current (Mont-
ery, 1938) carries water through the island passages into the
hern part of the Venezuelan Basin. This “North Atlantic”
er is close to Iselin's (1936: figs. 25 and 53) western Sargasso Sea
er in its temperature-salinity characteristics, though a trifle
her in part of the temperature range (Fig. 2). The deepest of
water which can enter the Caribbean does so through the Jung-
Passage, which, according to Frasetto and Northrop (1957),
a controlling sill depth of 1072 fathoms (1961 m).

n the southern part of the region (represented by the stations
t of the Windward Islands), the fresh tongue of the North At-
ic Equatorial Current (between 5 and something above 10° C;
to 1000 m) contains admixtures of Antarctic Intermediate
er which are significantly fresher than western Sargasso Sea
ter. The deepest sill along the Windwards, which according to
rdrup, *et al.* (1942) is between Dominica and Martinique, has a
th of less than 1500 m.

he Cariaco Trench is an isolated basin to the south of the Vene-
lan Basin. Its sill has a maximum depth of about 150 m, and
ow this depth the basin is so poorly ventilated that it has become
erobic and contains sulfides from about 400 m to the bottom at
out 1400 m (Richards and Vaccaro, 1956).

Silicate-Temperature-Salinity Relationships. The water masses of
Antilles Arc region have been characterized by plotting silicate
d salinity, respectively, against temperature (Fig. 2). These dia-
ms are useful, at temperatures below 7° C, in distinguishing
ter of four areas: (a) The eastern Venezuelan Basin; (b) The
lantic Ocean east of the southern islands of the Antilles Arc,
., the Windward Islands from Martinique to Tobago; (c) The
lantic Ocean north of the Antilles in the region of the Puerto
co Trench; and (d) The region of the Anegada and Jungfern Pas-
es between Puerto Rico and the Virgin Islands.

The waters of these areas colder than 10° C have been compared
h Iselin's (1936: figs. 25 and 53) temperature-salinity diagrams
the western Sargasso Sea, and salinity anomalies have been
nputed. Where these have a value greater than ±5, they have
n entered on the temperature-silicate diagram (Fig. 2).

Significant negative salinity anomalies, indicating admixture Antarctic Intermediate water, are accompanied by correspon ingly high silicates. Water of this type is found in the 6 to 7° range east of the Windwards, at the Anegada-Jungfern Passa stations, and in the Venezuelan Basin. It extends down to 5° east of the Windwards, but the 5 to 6° C water in the Anegad Jungfern Passage region and in the Venezuelan Basin tends to somewhat more saline, the latter being more like the Antarct Intermediate water than the former.

At temperatures colder than 5° C there are no significant salini anomalies in the Antilles Arc region, *i. e.*, all of the water mass have about the same temperature-salinity correlations. It is in t 4 to 5° C range that silicate concentrations are distinctive and clear distinguish the silicate-rich Caribbean waters from the silicate-po Atlantic waters, with the Anegada-Jungfern Passage samples bei of an intermediate character. Water colder than 4° C is absent fro the Caribbean, but such waters have similar silicate and salini characteristics in both of the Atlantic regions concerned. The st colder water in the depths of the Puerto Rico Trench continues increase in silicate to the greatest depths sampled.

Biochemical Relationships. The requirement of diatoms for lar quantities of silicate, the marked correspondence between diato outbursts and silicate depletion, and the preponderance of diatom among photosynthetic marine plants lead one to inquire into t possibility of relating the distribution of silicate in the ocean biological phenomena. Redfield (1934), Fleming (1940), Coop (1938), Gilson (1937) and others have demonstrated statistical co relations among inorganic phosphate, nitrate, carbon dioxide, and di solved oxygen in the water and the composition of marine organism (see Richards and Vaccaro, 1956, for a review). In the regions studie the concentration of silicate is also shown to be linearly related the regeneration of phosphate and nitrate and to oxygen consumptio in much of the water column. On the other hand, there are, in ac dition, hydrographic sources of silicate, not demonstrably related biological fixation and regeneration, which account for significa proportions of silicate, particularly in shallow and very deep water

Silicate-Phosphate Relationships. Plots of silicate as a function inorganic phosphate (Fig. 3) show that, at the intermediate dept

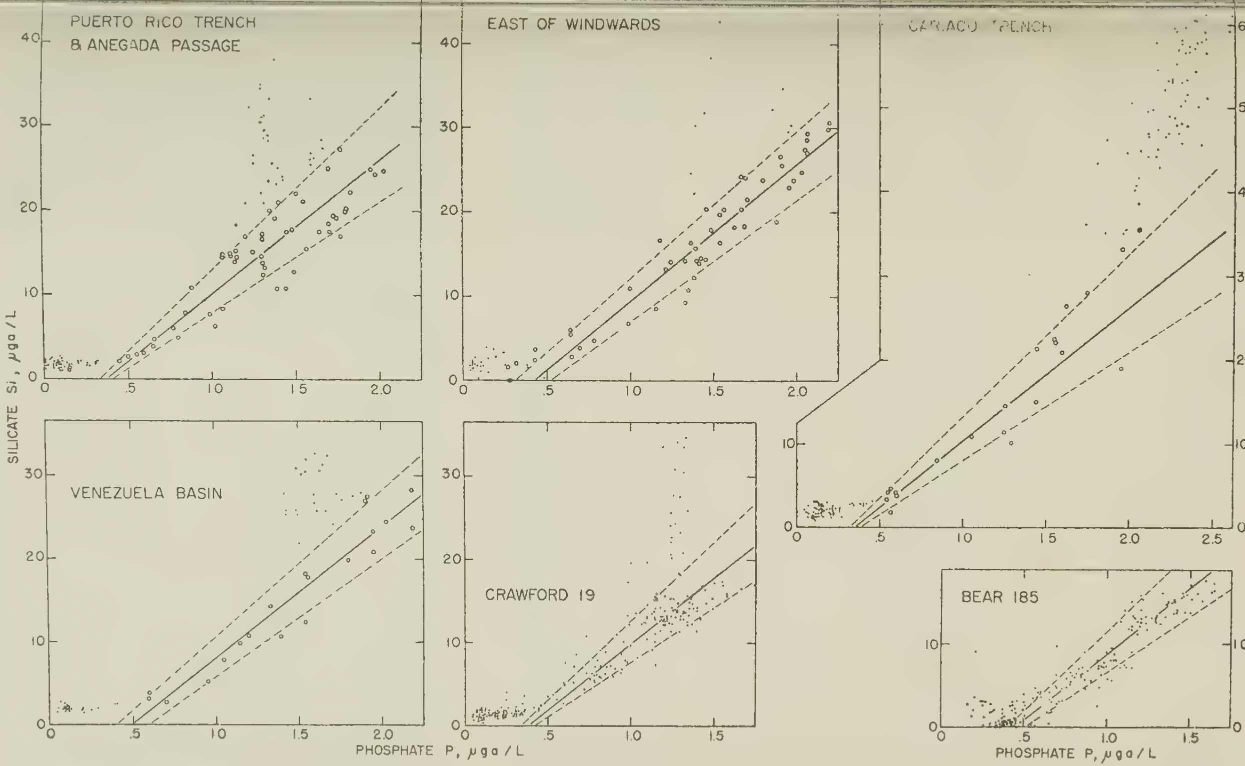


Figure 3. Silicate-phosphate relationships. The regression lines (solid) have slopes of ΔSi : ΔP = 16:1, by atoms. The broken envelope lines include all points along the regression lines with allowances for ± 9 % analytical errors in phosphate and ± 10 % in silicate. Open circles represent samples in which eq. (1) is assumed to be satisfied (see text).

listed in Table I and shown by open circles in Figs. 3 and 4, there a high degree of correlation between the two variables. At the depths, the ratio of change in phosphate and silicate has a near constant value, of approximately 16 atoms of silicate to one phosphate, *i. e.*,

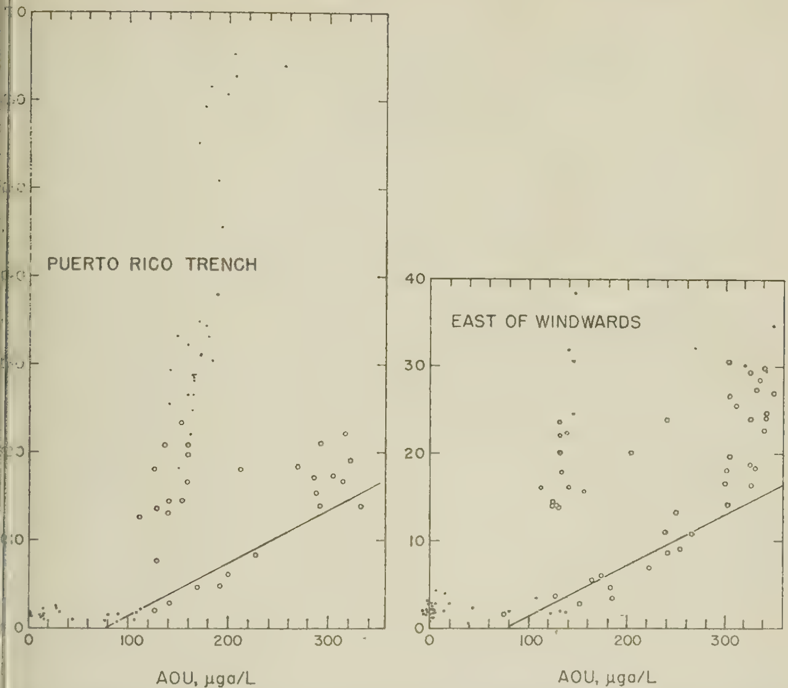
$$\Delta \mathrm{Si} = \mathrm{I} + 16 \times \Delta \mathrm{P}. \qquad ($$

In this equation, both silicate-silicon and phosphate-phorsphor concentrations are expressed in microgram atoms per liter. T value of the intercept, I, may vary from station to station and fro location to location, but it is not zero, emphasizing that the co stancy of ratio applies only to the rate of change in concentratio $\Delta \mathrm{Si}/\Delta \mathrm{P}$.

The above relationship holds neither in surface layers, which a low in both phosphate and silicate, nor in many of the deep wat samples, in which there are very high concentrations of silicate a high ratios of $\Delta \mathrm{Si}/\Delta \mathrm{P}$.

In the Cariaco Trench (Richards and Vaccaro, 1956), eq. (1) satisfied only in a thin layer just above the anerobic zone. The dept at which (1) is satisfied within an analytical range of $\pm 9\,{}^0/_0$ f phosphate and $\pm 10\,{}^0/_0$ for silicate, holding I constant, at the statio near the Antilles Arc, are shown in Table I and are indicated open circles in Figs. 1, 3 and 4.

Silicate-Oxygen Relationships. Redfield (1934, 1942) has demo strated relationships between the consumption of oxygen from s water (the AOU, apparent oxygen utilization, being the differen between the observed oxygen concentration and the concentrati which would be in equilibrium with the normal atmosphere at t *in situ* temperature and salinity), the regeneration of inorgan phosphate and nitrate, and the composition of plankton organism In view of the direct relationship which generally holds betwe phosphate and nitrate and in view of the similar relationship b tween silicate and phosphate, a close relationship between silica and oxygen consumption would be expected, and is found. Howev plots of silicate as a function of AOU (Fig. 4) indicate that in ma samples which satisfy (1) (indicated by open circles) there are lar departures from any simple linear relationship between silicate a AOU. These are samples containing appreciable quantities of p



ure 4. Silicate *vs* oxygen consumption (AOU) at stations in the Puerto Rico Trench he Atlantic Ocean east of the Windward Islands. Open circles correspond to those in 1 and 3.

ned[2] phosphate and preformed silicate which are present in the o of approximately 16 atoms of silicon to one atom of phosphorus. he plots of silicate against oxygen consumption indicate the ence, in upper waters, of a layer of variable thickness in which e is a low and relatively uniform concentration of silicate but which AOU values vary from nil to 80 or more µg-at/l.

ilicate-Nitrate Relationships. A fairly good positive correlation ts between nitrate and silicate concentrations observed between

---

Oxygen consumption is linearly related to the amount of phosphate (and ni-) regenerated on the decomposition of marine organisms. However, there may n additional amount of inorganic phosphate (and nitrate), which was in the ce water at the time it became saturated with oxygen and sank beneath the ce with its burden of organic matter. This phosphate (and nitrate) is referred y Redfield (1942) as "preformed".

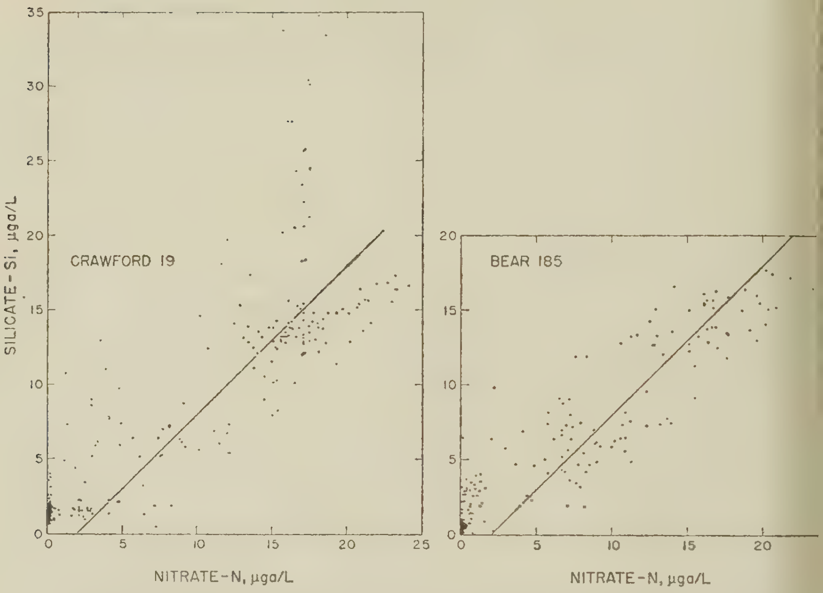


Figure 5. Silicate *vs* nitrate at stations between Woods Hole and Bermuda.

Woods Hole and Bermuda in May and July 1958 (Bear Cruise 1 and Crawford Cruise 19; see fig. 5), except in near-surface wate generally in both May and July and in the deep samples taken ne Bermuda in July. Though there is much scatter in these data, t ratio of change in silicate-silicon to nitrate-nitrogen is close to o for one, by atoms. In deep waters near Bermuda in July (not sampl in May), the Si/N ratio of 1/1 is greatly exceeded.

The near-surface samples from this region show different situatio prevailing during the two periods. The surface waters all have e cess quantities of phosphate, as shown by Ketchum, *et al.* (195 but concentrations of both silicate and nitrate are so low that o or the other or both may limit the further growth of planktonic ganisms. The May samples show low nitrates (< 2 μg-atN/l) acco panied by up to 4 μg-at/l of silicate-silicon. However, in July, ma of the low concentrations of silicate (< 2 μg-at/l) were accompani by up to 3 and, in a few cases, by over 5 μg-at/l of nitrate-nitroge This suggests that, in May, low concentrations of nitrate were mo probably limiting the growth of phytoplankton than low conce trations of silicate, while the opposite situation prevailed in Ju

iscussion. The distributions of silicate and other variables in
waters studied indicate that silicate may be directly related to
ogical regeneration in some of the strata and to hydrographic
ors in others. Direct relationships between silicate and the
ogically conditioned concentrations of phosphate, nitrate and
olved oxygen are generally found in an intermediate layer
reas different ratios between these variables are found in sur-
and deep waters, in water colder than about 5° C in the Vene-
an Basin, and in the anaerobic strata of the Cariaco Trench.
he ratios AOU: ΔC: ΔN: ΔP = 270:106:16:1 in sea water have
established by previous workers (Redfield, 1934; Gilson, 1937;
ing, 1940; Cooper, 1938; see Richards and Vaccaro, 1956). In
geographical areas and water masses described in this paper,
can now add: ΔSi:ΔP = 16:1, and ΔN:ΔSi = 1:1. These re-
nships hold in more samples than does the ratio ΔAOU:Si =
:1, which indicates that the values 16:16:1 for ΔN:ΔSi:ΔP
valid in samples which contain preformed phosphate and ni-
e; *i. e.*, there are larger concentrations of phosphate, nitrate, and
ate than would be expected from the amount of oxygen con-
ption.

ear-surface waters contain silicates in low concentrations which
y from place to place and from time to time, and the ratios of
ate to nitrate and to phosphate are also variable in these waters.
ween Woods Hole and Bermuda, where all three of these variables
e been studied, there is evidence (Ketchum, *et al.*, 1958) that
ganic phosphate was always present in sufficiently high concen-
ions that growth of planktonic organisms was not limited. On
other hand, either silicate or nitrate might have been limit-
for there is a suggestion in the data that first one and then the
er may be exhausted while nonlimiting concentrations of the
er are still present.

n many of the waters studied, particularly the deeper samples,
e are additional increments to the concentration of silicate,
ependent not only of the amount of oxygen consumption but also
he amounts of phosphate (and nitrate) regenerated. It appears
(1) silica re-solution may continue in deeper water after the
eration of phosphate (and nitrate) has gone to completion in
lower strata, or (2) there may be re-solution of silica from bot-
sediments with subsequent upward diffusion. These high silicate
centrations were observed in:

a. The Venezuelan Basin and Anegada Passage, where, betwe 4 and 5° C, they may arise from *in situ* re-solution of siliceous orga remains;

b. The Cariaco Trench, a special locus of isolated water in whi there has been extensive accumulation of silicate from re-soluti of siliceous materials; and

c. Deep Atlantic water; some of the increment in the deeper pa of the Puerto Rico Trench may also be of local, *in situ* origin.

The high silicate concentrations in the deep water of the Venezuel Basin constitute the most strikingly different water-mass chara teristic which has been observed to distinguish Caribbean a western North Atlantic water. However, Caribbean water is al more than 0.5 ml/l poorer in oxygen and somewhat richer in pho phate than the Atlantic water directly to the north. These are t kinds of chemical differences which distinguish the stagnant very poorly renewed deep water of the Cariaco Trench and whi one would expect to find in any stagnant or poorly flushed mari basin. For these reasons, it seems that, contrary to Sverdrup, *et* (1942: 640), the renewal of the deep water of the Venezuelan Bas must be a relatively slow, not a relatively rapid, process. Worthin ton's (1955) observations have pointed toward these same co clusions, which the silicate observations tend to corroborate.

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CHEMICAL COMPOSITION OF THREE MANGANESE NODULES FROM THE PACIFIC OCEAN[1]

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ABSTRACT

Three manganese nodules from the Pacific Ocean have been analysed for
elements by using mainly spectrophotometric and spectrographic methods. (
Co, Ni, Zn, and Pb were found in amounts approaching 1 $^{0}/_{0}$, which far excee
their average concentrations in igneous rocks. On the other hand, elements havi
readily hydrolysable ions, such as Ga, Sc, Zr, Y, La and Ti, are present only
amounts comparable with their concentrations in igneous rocks. Sb, Bi, Be, and
were not detected. The hydrochloric acid-insoluble fraction of nodules is practical
free of the heavy metals that are characteristic of the acid-soluble fraction; it co
sists principally of clay minerals, together with lesser amounts of quartz, apati
biotite and sodium and potassium felspars.

INTRODUCTION

One of the most interesting problems of marine geochemistry
the origin of the manganese deposits which have formed over lar
areas of the deep ocean floors. These deposits occur either as dar
coloured grains and coatings on the sea bed and on the debris abo
it, or as discrete concretions (so-called manganese nodules) whi
were first discovered during the CHALLENGER Expedition of 187
76 (36).

Although manganese nodules are quite scarce in the Atlant
Ocean, where the sediment is poor in manganese, they are found
great abundance in some areas of the Pacific Ocean, where th
have frequently been recovered in amounts as great as 50–100 k
They usually occur in water deeper than 2000 m, but occasional
they have been found in water as shallow as 260 m (37). Nodul
appear to be more abundant (25) on the top of outcrops of pr
Pleistocene sediments and on elevated areas of the ocean floor th
in the surrounding depressions.

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[1] The authors wish to thank the trustees of the British Museum (Natural Histo
for the gift of nodules taken at CHALLENGER Sts. 248 and 252.

odules are found principally on red clay deposits and are par-
larly abundant on the dark chocolate-coloured oozes which are
in manganese. They also occur less frequently on radiolarian
globigerina ooze and even in blue muds formed under conditions
ow redox potential (CHALLENGER Sts. 298 and 299).

odules, which vary in shape from almost spherical and ovoid
through irregular shapes to flattened slabs, occur in a wide
ge of sizes; spherical types range from 0.5 to 15 cm in diameter
flattened types may reach a size of 20 × 50 × 4 cm. Their sur-
s, frequently reniform, appear to have been formed by amal-
ation of a number of small nodules. In general, all nodules from
rticular locality are roughly similar in shape but may differ
tly in size.

enerally, but not always, nodules are formed around a nucleus
ifferent material which consists most frequently of pumice, vol-
ic glass or igneous rock, often much altered; less commonly,
nuclei consist of shark or fish teeth (sometimes those of extinct
cies), otoliths and bones of Cetaceans, or siliceous and calcareous
nges (2).

The majority of manganese nodules are built up of a series of
centric layers of alternating light and dark bands, which show
concretionary nature of the nodules. Sometimes, particularly in
se specimens containing no nucleus, only the outer parts are
nded, the inner part appearing homogeneous and much darker
colour. The concentric structure is often combined with a radial
ucture in which dendritic growths of manganese oxide penetrate
vards through several layers. The various forms of nodules and
eir internal structures are clearly shown by Murray and Renard
: pls. I–IV, IX).

Chemically, the external portions of nodules consist principally
hydrated oxides of manganese and iron, in varying proportions,
gether with significant amounts of many other elements, partic-
rly transition metals. They also contain variable amounts of
ventitious matter, such as clay and mineral grains. Few of the
ly analyses of manganese nodules (36, 2) are satisfactory; fre-
ently, major constituent elements were not determined, and in
ny cases the nucleus was included in the sample analysed.

The only reasonably complete analysis of a manganese nod-
which can be traced is that by Gibson (36: 416–423), who
termined 28 elements in some small nodules from the Pacific

(Challenger St. 285). Owing to the rather primitive techniqu available in his time, the analysis must be considered only sem quantitative, but it did draw attention to the presence of conside able amounts of certain rare elements that are present in nodule

Goldberg (14) has analysed nodules from 11 localities in tl eastern Pacific Ocean for iron, manganese and nine other element His results (see Table I) represent the composition of the nodul (presumably excluding the nucleus but including any interstiti silicate). They show Fe/Mn ratios varying from 0.26 to 1.28 ar demonstrate the considerable enrichment of manganese, copper, c balt and nickel in the nodules compared with red clay or avera igneous rocks. Goldberg claims he found linear relationships of tl iron content with the titanium, zirconium and cobalt contents ar of manganese with copper and nickel. Statistical examination of h figures reveals that there is no correlation of iron with zirconiu or of manganese with copper, although there is a high degree probability of a correlation of iron with titanium and cobalt.

TABLE I. Composition of Pacific Ocean Manganese Nodules in Percen of Weight

Element	*Gibson, in Murray & Renard,* 36	*Goldberg,* 14		
		Minimum	*Maximum*	*Average*
Iron	10.00	6.18	20.3	13.8
Manganese	16.66	10.8	24.2	19.0
Nickel	0.77	0.16	1.15	0.46
Cobalt	0.22	0.066	0.71	0.28
Copper	0.30	0.17	1.81	0.55
Phosphorus	0.06	0.22	1.97	0.54
Aluminium	2.90	0.27	1.70	0.73
Titanium	0.06	0.27	1.25	0.81
Zirconium	—	0.0038	0.014	0.0064

Dietz (13) has discussed the occurrence of manganese concretion and nodules on the northeastern Pacific sea floor. He has presente analytical data for iron, manganese, cobalt and nickel in two nodul and three manganese crusts. One of these crusts (from the Gilbe Sea Mount) contained 3.1 $^0/_0$ CaO; 1.9 $^0/_0$ MgO; 8.4 $^0/_0$ SiO_2; 3.2 ^{0} Al_2O_3; 0.50 $^0/_0$ P_2O_5; 0.13 $^0/_0$ V_2O_5; 0.90 $^0/_0$ TiO_2; 0.20 $^0/_0$ Mo; 0.55 ^{0} S; 0.06 $^0/_0$ Cu; 11.0 $^0/_0$ insoluble.

ldberg and Arrhenius (15) have published spectrographic data
e composition of a concretion which had formed around a steel
nent at a depth of 2000 m. This concretion was mainly com-
l of hydrous iron oxides together with 0.1 $^0/_0$ of manganese and
eciable amounts of metals characteristic of manganese nodules.
merous determinations of particular trace elements in man-
se nodules have been carried out (Table II), particularly in
ection with determinations of their rate of formation based
eir content of radioactive elements.

E II. OCCURRENCE OF TRACE ELEMENTS IN MANGANESE NODULES FROM THE PACIFIC OCEAN

Element	*μg of Element per gm*	*Reference*
Beryllium	Not detected*	21
Boron	500*	22
Cadmium	8–13	34
Gallium	4*	19
Lead	3450	39
Lead	27–2180 (mean 1740)	9
Niobium	24	42
Radium	1.2–25 × 10^{-6}	40
Radium	up to 80 × 10^{-6}	8
Scandium	4*	20
Thorium	1.3	29
Thorium	38–143	33
Thorium	24–124	16
Yttrium	10*	20

CHALLENGER Expedition St. 286.

ntil recently nothing has been known of the structure of iron
manganese compounds comprising the bulk of nodules, since
give only diffuse lines by the normal X-ray diffraction methods.
a valuable paper, Buser and Grütter (1) have shown that, in
ules containing only small amounts of iron, most of the man-
ese is in the form of δ-manganese dioxide together with manga-
II manganite [$3\,MnO_2\,Mn(OH)_2 \times H_2O$]. The latter compound
a double layer structure; the main layers, which contain Mn^{4+}
ix-fold co-ordination with O^{2-}, are separated by 10 Å and con-
between them a disordered layer of Mn^{2+} co-ordinated with
, OH^- and H_2O. In nodules containing iron, the Mn^{2+} in this
rmediate layer is replaced by Fe^{3+} to form ferric manganite,

and some of the Mn^{4+} ions in the main layers may also be replac
by Fe^{3+} with the development of a charge. The majority of nodu
contain more iron than can be accomodated as ferric mangani
and this is held as the highly adsorptive hydroxide, part of whi
may be converted into goethite (α-FeOOH). The Mn^{2+} in the int
mediate layer may also be replaced by other polyvalent ions (su
as those of cobalt, nickel, and the rare earths) with a high cha
density. This probably explains the high concentrations of th
elements in manganese nodules.

The mode of formation of manganese nodules has been the su
ject of much discussion, and the literature on their formation
been critically reviewed by Pettersson (41) and by Goldberg a
Arrhenius (15). The latter workers postulate that positively charg
colloidal hydrated iron oxide particles are deposited electrophor
ically on oppositely charged nuclei, such as pumice, sharks' tee
etc. The electropotentials of these nuclei are attributed to the fl
of ocean water (a conductor) through the earth's magnetic fi
(*cf.* 14). Manganous ions brought to the sediment-water interface
various physical processes are oxidised to tetravalent mangan
by oxygen under the catalytic action of the discharged iron oxi
colloid. This tetravalent manganese oxide associates with the ca
lyst and, to a lesser extent, with divalent manganese hydroxide
form manganous and ferric manganites found by Buser and Gr
ter (7).

While this theory gives a possible explanation of the mechani
of formation of the commonest types of nodules in which the Mn:
ratio varies from *ca.* 1.5 to 4, it can not explain the existence
nodules with a ratio of 55 (0.8 $^0/_0$ Fe), such as that cited by Bu
and Grütter (ALBATROSS St. 373).

The rate of accretion of manganese nodules has been estima
by Pettersson (40) and by von Buttlar and Houtermans (8) to
ca. 0.6–1.3 mm per thousand years. This figure must be regarded
minimal, since it is based on the assumption that all of the radiu
present in nodules was derived from seawater. The high thoriu
content of nodules, however, suggests that the ionium in sea wa
derived from uranium decay is also collected, and this in its tu
will produce radium and so give an over-estimate of the rate
deposition (15).

In view of the small amount of reliable data on the occurrence
many of the less abundant elements in manganese nodules, specim

ted by the CHALLENGER Expedition at three stations in the ic Ocean were analysed for 35 elements. In each case the nu- of the nodule was removed before analysis. The origin of each le is shown in Table III and descriptions of each are given below.

E III. ORIGIN OF MANGANESE NODULES. ALL SAMPLES WERE TAKEN FROM A SEDIMENT OF RED CLAY

Challenger	*Brit. Mus. Catalogue No.*	*Position*		*Depth (m)*
		Lat.	*Long.*	
St. 248	M 313	37°41′ N	177°04′ W	5304
St. 252	M 316	37°52′ N	160°17′ W	5011
St. 276	—	13°28′ S	149°30′ W	4298

DESCRIPTIONS OF NODULES ANALYSED

HALLENGER *St. 248.* At this station a large number of manga- nodules, together with many pumice stones and sharks' teeth, collected by trawl. The specimen examined, *ca.* 7.5 cm in di- ter, had a nucleus of much altered pumice surrounded by alter- ng light and dark bands. It was similar in external and internal cture to nodules shown by Murray and Renard (36: plate II, l; plate IX, fig. 4) and was typical of the majority of samples nd at this station.

HALLENGER *St. 252.* Hundreds of rounded or ellipsoidal manga- nodules were collected at this station, the largest ones being 8–9 cm in diameter. The specimen examined, almost spherical a diameter of *ca.* 7.5 cm, consisted of three zones: (i) a hard owish nucleus penetrated by dendrites of manganese; (ii) a dark r of manganese oxides about 0.8 cm thick, (iii) an outer zone concentric structure separated from the inner layer by a thin d of clay (?). This structure is analogous to that found by Mur- and Renard (36) for other nodules from this station.

HALLENGER *St. 276.* About 200 l of small manganese nodules, ks' teeth, otoliths, pumice stones, and volcanic rock were taken his station. The sample used for analysis consisted of five small almost spherical nodules, having diameters ranging from 2–3 cm, ely resembling those shown by Murray and Renard (36: plate IV, 7, 8). All had yellowish nuclei of much altered volcanic rock.

EXPERIMENTAL

Preparation of Samples. Each nodule was cut into sections, t nucleus and other heterogeneous materials were removed, and was then powdered to pass through an 80 mesh sieve. In order remove any interstitial salts derived from seawater (*e. g.*, the sam from Ch. St. 276 contained 0.50 $^0/_0$ Cl$^-$ and 0.47 $^0/_0$ SO_3), the pow ered sample was boiled in 200 times its own weight of water. T cold liquid was allowed to stand overnight. The residue, separat by filtration, was washed with hot water and then dried at 11 in each case the sample contained less than 0.01 $^0/_0$ Cl$^-$ and 0.02 acid-soluble SO_3.

Separation of the acid-insoluble fraction. The fine powder (10 was treated with 50 ml of concentrated hydrochloric acid and eva orated to dryness on the waterbath. The dry residue was treat with 15 ml of perchloric acid and heated on a hot plate until den white fumes were evolved. When the sample had cooled, 200 ml 0.5 N perchloric acid were added; this mixture was then heated the waterbath with constant stirring, and the liquid was filter through a weighed sintered glass crucible. The insoluble resid after it had been thoroughly washed by decantation, was transferr to the filter, dried at 110°, and reweighed. The filtrate and washin were combined and diluted to 500 ml; this solution was used the determination of most of the elements of the acid-solub fraction.

Analysis of the insoluble fraction. Determination of the princip components of the insoluble fraction was carried out as described Riley (45). Trace elements were determined spectrographically (

Analysis of the acid-soluble fraction. The methods used to det mine elements in the acid-soluble fraction are summarised in Table I In general, the analyses were performed on the solution prepar as described above. In certain cases, however, when spectrograph determinations were made or when volatile elements (such as chro ium, boron, or germanium) were determined, the powdered nod was used. The amount of the element in the soluble part was es mated by subtraction of its weighted concentration in the insolu part.

E IV. SUMMARY OF METHODS OF ANALYSIS USED FOR ACID-SOLUBLE FRACTION OF MANGANESE NODULES

ent	*Method*	*Reference*
nium	Spectrophotometric, as aluminium oxinate	45
ony	Spectrographic – detection limit 30 ppm	
ra	Spectrographic	1
ium	Spectrographic – detection limit 10 ppm	1
th	Spectrographic – detection limit 10 ppm	
	Spectrophotometric, as boron-turmeric complex	Unpublish.*
um	Spectrophotometric, as dithizonate	34
n	Gravimetric, as oxalate	51
um	Spectrophotometric with diphenylcarbazide	48
	Spectrophotometric, as thiocyanate	48
r	Spectrophotometric, as diquinolyl complex	47
n	Spectrophotometric, as Rhodamine B chlorogallate	12
anium	Spectrophotometric, as phenylfluorone complex	6
	Volumetric	30
anum	Spectrographic	1
	Spectrophotometric, as dithizonate	48
esium	Gravimetric, as magnesium pyrophosphate	51
anese	Volumetric (potentiometric titration)	32
denum	Spectrophotometric, as thiocyanate	48
l	Spectrophotometric, as dimethylglyoxime complex	48
horus	Spectrophotometric, as molybdenum blue complex	35
ssium	Flame photometric	45
ium	Spectrographic	1
r	Spectrographic	1
m	Flame photometric	45
tium	Spectrographic	1
ium	Spectrographic	1
	Spectrographic	1
ium	Spectrophotometric, with hydrogen peroxide	48
sten	Spectrophotometric, as thiocyanate	48
dium	Spectrophotometric, as oxinate	48
um	Spectrographic	1
	Spectrophotometric, as dithizonate	48
nium	Spectrographic	1
able oxygen	Volumetric	30
r	Gravimetric	46
on dioxide	Gravimetric	46

Greenhalgh and Riley.

TABLE V. COMPOSITION OF ACID-INSOLUBLE MATTER FROM MANGANESE NODU
DRIED AT 110°. PERCENT BY WEIGHT

	Challenger Stations		
	248	*252*	*276*
% Insol.	32.61	26.09	32.19
SiO_2	73.90	72.10	72.70
Al_2O_3	10.16	10.65	10.89
Fe_2O_3	0.93	1.00	1.01
TiO_2	0.55	0.60	0.54
MnO	0.02	0.02	0.02
P_2O_5	0.33	0.25	0.19
CaO	0.94	0.91	0.89
MgO	0.64	0.80	0.63
Na_2O	2.08	2.32	2.16
K_2O	1.50	1.80	1.71
H_2O	8.90	10.00	9.10
	99.95	100.45	99.84

MINOR ELEMENTS (PPM)*

St. No.	*Ba*	*Co*	*Cu*	*Ga*	*Ni*	*Pb*	*Sn*	*Sr*	*V*
248	260	3	30	3	6	5	<10	80	25
276	200	3	20	4	5	5	<10	110	18

* Ag, Be, La, Mo, Sc and Tl not detected.

DISCUSSION

The nodules examined contained between 26 and 33 % of ac
insoluble material of similar composition (see Table V). Microsco
examination of thin sections of the nodules showed the presence
large amounts of clay minerals together with small amounts
quartz grains, apatite needles, hornblende and low temperat
sodium or potassium felspar. These minerals were concentrated
the light coloured concentric bands. The rather drastic method us
for the removal of the acid-soluble part of the nodules has proba
caused a loss of some sodium and potassium and of lesser amou
of other elements from the clay minerals, hence their amounts
the insoluble matter may be slightly underestimated.

With the exception of barium, titanium and zirconium, the
soluble fractions were almost free of those elements which
strongly concentrated in the soluble fraction. It is probable t

three elements occur in the nodules in the form of barite, and zircon, respectively, which were derived from red clay ich the nodules were found. These minerals are unreactive and ble and occur in most Pacific Ocean deposits in appreciable nts.

alyses of the acid-soluble parts of the nodules are shown in VI together with the abundance of relevant elements in sea- r and the concentration factors (mean concentration [in ppm] ement in soluble fraction of nodule/concentration [ppm] of nt in sea water).

penultimate column of figures in Table VI was compiled after cal survey of the data for the abundance of elements in sea r, collected by Richards (44). No values were available for the ntration of many trace elements in deep ocean waters. In such values for surface or near surface waters were used; it must alised that such samples may be quite different in trace metal ent from those obtained in deep water. Hence there may be an of about one order of magnitude in the concentration factors n.

e concentrations of manganese and iron found in the three les examined were similar to the averages given by Sverdrup (50) were greater than any of those reported by Goldberg (14). Many e minor elements, such as zinc, copper, nickel and lead, are h enriched in the soluble part of the nodules compared with the sphere and are present in economically recoverable amounts. values for nickel and cobalt agree well with the linear relation- s found by Goldberg between manganese and nickel and be- n cobalt and iron concentrations respectively.

e average Co/Ni ratio for the nodules (0.38) is close to the value .40 found by Goldschmidt (18) for hydrolysate sediments. The Cd ratio (660) is similar to that found for igneous rocks (530); rently little differentiation of the two elements occurs during hering, transport to the sea, adsorption and deposition in the les.

elative to the iron content, the titanium and zirconium concen- ions are lower and higher respectively than those reported by lberg. The amounts of gallium, scandium and yttrium are about times greater than those found by Goldschmidt and Peters a nodule from Challenger St. 286 (Table II). The concentra- s of these elements and those of a number of others, such as

TABLE VI. COMPOSITION OF ACID-SOLUBLE FRACTION OF MANGANESE NODULES

		Weight °/₀ Oxides in Soluble Fraction			Weight °/₀ Element Excluding H_2O and $CaCO_3$			Mean	Conc. of Element in Sea Water (μg/l)	Concn. Factor	Reference
CHALLENGER St.		248	252	276†	248	252	276	—	—	—	—
Soluble Percent		67.39	73.91	67.81	—	—	—	—	—	—	—
Element	*Oxide*										
Aluminium	Al_2O_3	6.04	2.00	4.72	4.23	1.36	3.27	2.95	10	3×10^6	49
Antimony	Sb_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—	—	—	—
Barium	BaO	0.58	0.51	0.41	0.69	0.59	0.48	0.59	50	1×10^5	17
Bismuth	Bi_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—	0.2	—	38
Beryllium	BeO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—	0.03	—	28
Boron	B_2O_3	0.010	—	0.013	0.004	—	0.005	0.005	4500	11	50
Cadmium	CdO	0.0011	—	0.0007	0.0013	—	0.0008	0.0010	0.1	1.0×10^5	34
Calcium	CaO	2.10	1.54	3.49	0.42	0.01	0.40	0.27	4×10^5	6.7	50
Chromium	Cr_2O_3	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.05	$<10^5$	27
Cobalt	CoO	0.17	0.22	0.28	0.17	0.22	0.29	0.23	0.4	5.0×10^6	27
Copper	CuO	0.80	0.44	0.45	0.85	0.45	0.47	0.59	2***	3×10^6	4
Gallium	Ga_2O_3	0.0029	0.0021	0.0025	0.0029	0.0021	0.0023	0.0024	0.03	8×10^5	11
Germanium	GeO_2	0.0007	—	0.0009	0.0007	—	0.0008	0.0007	0.06	1.2×10^5	6
Iron	Fe_2O_3	21.44	23.73	28.60	19.85	21.34	26.14	22.44	<1.0**	$>2.2\times10^7$	3
Lanthanum	La_2O_3	0.02	0.01	0.03	0.03	0.02	0.04	0.03	0.3	10^6	17
Lead	PbO	0.15	0.22	0.25	0.19	0.26	0.30	0.25	5	5×10^5	38
Magnesium	MgO	0.90	0.10	0.01	0.71	0.08	0.01	0.27	1.3×10^6	2.1	50
Manganese	MnO	31.62	34.73	28.79	32.41	34.57	29.14	32.04	ca. 1***	3.2×10^8	26

Nickel	NiO	0.53	0.69	0.53	0.56	0.69	0.55	0.60	2	3×10^6	31
Phosphorus	P_2O_5	0.30	0.27	0.34	0.17	0.15	0.20	0.17	variable	—	—
Potassium	K_2O	1.45	1.45	1.33	1.60	1.54	1.40	1.51	3.8×10^5	40	50
Scandium	Sc_2O_3	0.0015	0.0008	0.0015	0.0013	0.0006	0.0010	0.0010	0.04	3×10^5	17
Silver	Ag_2O	0.0016	0.0015	0.0015	0.0020	0.0018	0.0020	0.0019	0.15	1.3×10^5	38
Sodium	Na_2O	3.37	2.56	2.56	3.30	2.44	2.48	2.74	1.05×10^7	2.6	50
Strontium	SrO	0.18	0.09	0.07	0.20	0.10	0.08	0.13	8×10^3	1.6×10^2	10
Thallium	Tl_2O	0.009	0.011	0.008	0.012	0.014	0.010	0.013	<0.01	$>10^7$	38
Tin	SnO_2	0.03	0.04	0.03	0.03	0.04	0.03	0.03	3	1.0×10^5	38
Titanium	TiO_2	0.56	1.11	0.71	0.45	0.85	0.56	0.56	1	6×10^6	23, 24
Tungsten	WO_3	0.006	—	0.012	0.007	—	0.010	0.009	0.1	0.9×10^6	27
Vanadium	V_2O_5	0.071	0.071	0.125	0.053	0.051	0.090	0.064	3	2×10^5	27
Yttrium	Y_2O_3	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.3	1.0×10^5	17
Zinc	ZnO	0.70	0.51	0.67	0.74	0.53	0.70	0.66	5	1×10^6	17
Zirconium	ZrO_2	0.015	0.014	0.012	0.015	0.010	0.012	0.012	—	—	—
Available oxygen		6.10	7.40	6.10	—	—	—	—	—	—	—
Water	H_2O	22.43	20.75	18.47	—	—	—	—	—	—	—
Carbon dioxide	CO_2	1.30	1.20	2.40	—	—	—	—	—	—	—
Oxide oxygen		—	—	—	33.25	34.63	33.28	—	—	—	—
Totals		100.08	99.76	100.48	100.00	100.00	100.00	—	—	—	—

† Sample 276 also contained 2.3 ppm HgO_2, 62 ppm ThO_2 and 110 ppm CeO_2 in whole nodule.

* Concentration factor = mean concentration of element in nodules (μg/g) / concentration of element in sea water (μg/ml).

** Very variable—figure given is for average total iron, in samples from depths of more than 2000 m.

*** Known to be very variable.

zirconium and vanadium, are similar to their abundances in lithosphere.

Since the majority of the minor elements of the nodules probably adsorbed directly from sea water (15), a consideration the concentration factors should prove useful. These factors ra from over 3×10^7 for manganese and iron down to values of less tl 40 for elements which occur in major amounts in sea water. The lat elements are mainly those forming hydroxides with ionic bor which, according to Wickman (52), are not strongly adsorbed; tl amounts in the soluble part are relatively small. It is almost cert that some of the sodium and potassium shown in the analy (Table VI) has been dissolved from the insoluble fraction during opening up of the nodules.

The majority of other elements have concentration factors ly between 10^5 and 10^6. These include elements occurring in sea wa in a cationic form as well as elements co-ordinated with chlorine oxygen, such as copper or tungsten and vanadium (43) respective which occur as anions. Elements such as scandium, titanium zirconium, which have ions that are readily hydrolysed, proba exist in sea water in the form of positively charged colloidal hydra oxides (43: 235). Such colloidal particles are probably readily sorbed by oppositely charged manganite or other particles.

Elements such as cobalt, nickel, copper, zinc and lead, which strongly concentrated in the nodules and which have high conc tration factors, probably occur in sea water in ionic form, either cations or as anionic chloro-complexes. These elements, which h high charge densities, are probably removed from sea water chemisorption on colloidal ferric hydroxide or on the intermedi layers of the manganites, as described by Buser and Grütter

The presence of appreciable amounts of thallium in the nodu is of interest, since this element has not been detected in seawa Unpublished work in these laboratories has shown that its conc tration is less than 0.01 μg/l. In the nodules, thallium is proba in the trivalent state on account of their high redox potential.

Antimony, bismuth and beryllium were sought spectrographic but were not detected in any of the nodules; their concentrati must be less than *ca.* 10 ppm. In addition, chromium was not tected either chemically or spectrographically and its concentrat must be less than 5 ppm; the absence of chromium is rather prising since it occurs in amounts varying from 0.003 to 0.01 $^0/$

gic red clay (Unpublished) and since Goldberg and Arrhenius found 0.002 °/₀ in a ferric oxide concretion. The redox potential ne nodules is sufficiently high to ensure that any chromium ent is oxidised to the chromate ion.

e atomic ratios Mn/available oxygen lead to the formulae $_{1\cdot86}$, $MnO_{1\cdot94}$ and $MnO_{1\cdot94}$ for the oxide of manganese in the ies from CHALLENGER Sts. 248, 252 and 276 respectively. These iences of oxygen are in agreement with structures of the ferric manganous manganites which constitute the nodules. On the r hand, Dittmar (36) found an O:Mn ratio slightly greater 2; this is probably attributable to errors in the analytical od used for the determination of manganese.

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HARACTERISTICS AND FLOW PATHS OF THE INTERMEDIATE DEPTH WATERS OF THE SOUTHEAST INDIAN OCEAN

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ABSTRACT

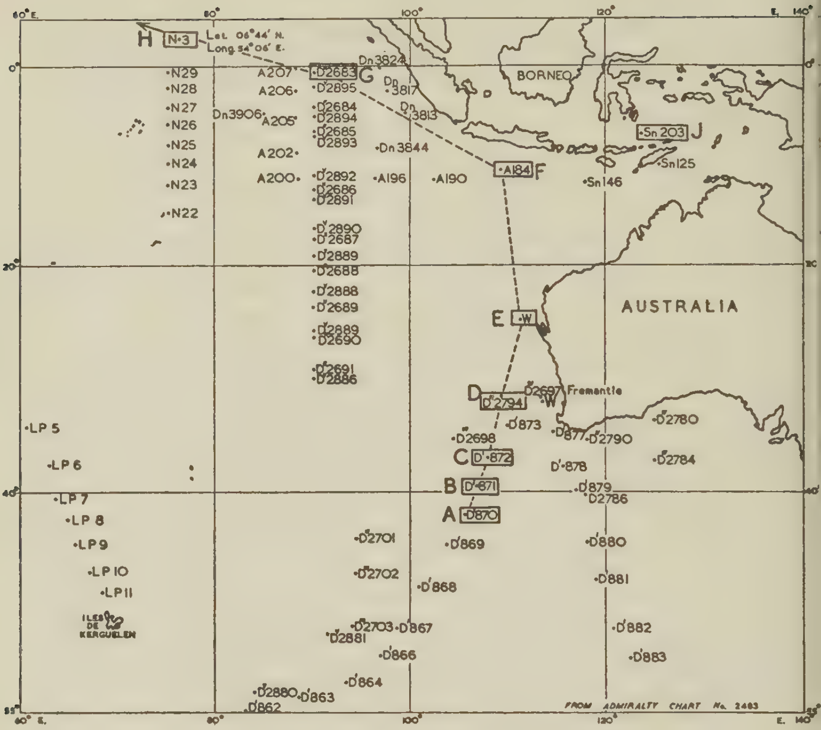
For the southeast Indian Ocean, isentropic analysis of salinity and oxygen istributions on the 27.20 and 26.80 σ_t surfaces showed that mixing of sub-Antarctic ntermediate water with poorly oxygenated bottom water of Arabian Sea origin as confined to the region west of about 90° E, east of which there was sinking nd movement of oxygenated waters from tropical and subtropical convergences nd from the Banda Sea. The seasonal change of properties on the 27.20 and 26.80 σ_t urfaces off Fremantle gave some indication of the seasonal flow paths of these ifferent waters.

INTRODUCTION

Between 1947 and 1951 the F.R.V. WARREEN occupied hydrological stations to depths of 1000 m off southwest Australia between Shark Bay and Albany. In August 1950 and in January 1951 R.R.S. DISCOVERY II sampled waters between the Great Australian Bight and Fremantle (Fig. 1). Thereafter this Laboratory's oceanic hydrological programme in southwest Australia was terminated.

TABLE I. SOURCES OF DATA UTILIZED

Year	*Month*	*Vessel*	*Reference*
1929	IX–X	DANA	1
1929	I–XI	SNELLIUS	13
1932	IV–V	DISCOVERY II	2
1948	III–IV	ALBATROSS	5
1948–50	—	WARREEN	6
1950	VI	DISCOVERY II	3
1950	VIII	DISCOVERY II	3
1951	I	DISCOVERY II	8
1951	IX–X	DISCOVERY II	3
1951	—	WARREEN	7
1956	I	LAPÉROUSE	4
1956	II–III	NORSEL	12


60° E.
80°
100°
120°
E. 140°
0°
20°
40°
55°
H
N·3
Lat. 06°44′ N.
Long. 54°06′ E.
·N29
·N28
·N27
·N26
·N25
·N24
·N23
·N22
A207
A206·
A205·
A202·
A200·
Dn3906
·D2683
G
·D2895
·D2684
·D2894
·D2685
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·D2892
·D2686
·D2891
·D2890
·D2687
·D2889
·D2688
·D2888
·D2689
·D2889
·D2690
·D2691
·D2886
Dn3824
Dn 3817
Dn 3813
·Dn 3844
·A196
·A190
·A184
F
BORNEO
·Sn 203
J
·Sn125
·Sn146
AUSTRALIA
E
·W
D
·D2794
·D2697
·W
Fremantle
·D873
·D2698
C
·D·872
·D877
·D2790
·D2780
·D2784
D·878
B
D·871
·D879
D2786
A
·D870
·D869
·D880
·D881
·D2701
·D2702
·D868
·D882
·D883
·D2703
·D867
D2881
·D866
·D864
·D2880
·D863
D862
·LP 5
·LP 6
·LP 7
·LP 8
·LP 9
·LP 10
·LP 11
ILES DE KERGUELEN
FROM ADMIRALTY CHART No. 2483

Figure 1. Location of stations:

Symbol	*Vessel*	*Month*	*Year*
A	ALBATROSS	III–IV	1948
Dn	DANA	IX–X	1929
DI	DISCOVERY II	IV–V	1932
DII	DISCOVERY II	VI	1950
DIII	DISCOVERY II	VIII	1950
DIV	DISCOVERY II	I	1951
DV	DISCOVERY II	IX–X	1951
L.P.	LAPÉROUSE	I	1956
N	NORSEL	II–III	1956
Sn	SNELLIUS	X–XI	1929
W	WARREEN	XII	1948

Lettered stations within squares are those used in Fig. 15.

The hydrological properties of this region varied considerably withi the 500–1000 m levels. This paper examines the seasonal nature c these variations and shows their probable relationship to the inter mediate circulation of the southeast Indian Ocean.

Table I lists the published sources of data from which the stations hown in Fig. 1 were selected. The method originally used by Montomery (9) for interpreting flow patterns from the bathymetry and istribution of properties on isopycnal or near-isentropic surfaces was llowed. The assumptions in his method have been accepted.

VARIATIONS IN HYDROLOGICAL PROPERTIES OF WATERS OFF FREMANTLE

The salinity-temperature relationship of waters west of Fremantle ig. 2) showed the presence of two types of water to the limit of mpling depths. The water with the higher salinity and temperature n corresponding σ_t surfaces (Fig. 2) had a higher oxygen saturation Fig. 3) and lower total phosphorus content (Fig. 4) than the other.

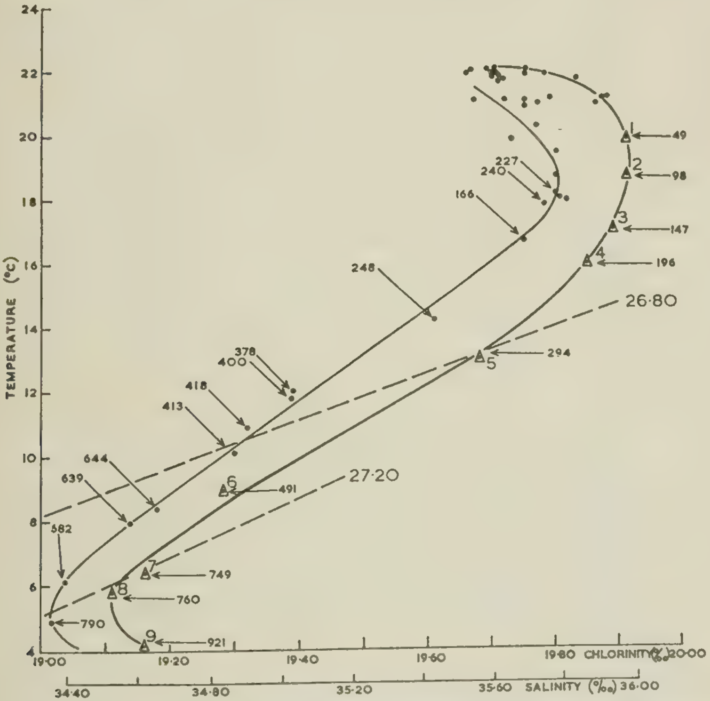


Figure 2. Salinity-temperature relationships of waters off Fremantle, February 1951. The numbered triangles enclose points which are referred to in Figs. 3 and 4. Selected depths are also given.

TABLE II. DEPTH, SALINITY AND OXYGEN VALUES ON THE 27.20 σ_t SURFACE AT A SERIES OF FIVE LONGITUDES WEST OF FREMANTLE, 1948–51. BOLDFACE VALUES INDICATE STATIONS AND MONTHS WHEN HIGH SALINITY, WELL OXYGENATED WATERS OCCURRED

Date	113°30′ E			114°17′ E			114°41′ E			114°53′ E			115°05′ E		
	Depth	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2
16/4/48	—	—	—	710	34.50	4.59	780	34.51	4.80	—	—	—	—	—	—
24/8/48	800	34.47	4.79	—	—	—	750	34.79	5.30	—	—	—	—	—	—
11/12/48	520	34.52	4.74	735	34.47	4.39	580	34.67	5.14	—	—	—	—	—	—
6/4/49	830	34.63	5.04	735	34.71	4.94	693	34.67	5.05	735	34.67	4.73	—	—	—
7/6/49	405	34.92	5.72	—	—	—	809	34.53	4.74	—	—	—	—	—	—
22/7/49	**324**	**35.88**	**5.76**	650	34.88	5.21	587	34.77	5.09	755	34.42	4.68	—	—	—
9/11/49	872	34.38	4.80	856	34.53	5.11	862	34.49	4.96	—	—	—	—	—	—
23/2/50	780	34.68	5.20	656	34.48	5.17	850	34.38	4.65	—	—	—	—	—	—
21/6/50	—	—	—	770	34.66	5.12	**520**	**35.01**	**5.66**	—	—	—	—	—	—
5/10/50	696	34.55	4.83	840	34.45	4.55	760	34.50	4.76	—	—	—	**583**	**34.93**	**5.68**
18/1/51	900	34.41	4.18	790	34.48	4.39	—	—	—	—	—	—	—	—	—
23/2/51	735	34.62	5.28	790	34.36	4.23	752	34.53	4.84	—	—	—	—	—	—
6/7/51	850	34.43	4.63	893	34.42	4.56	—	—	—	—	—	—	—	—	—

TABLE III. DEPTH, SALINITY AND OXYGEN ON THE 26.80 σ_t SURFACE AT A SERIES OF FIVE LONGITUDES WEST OF FREMANTLE, 1948–51. BOLD FACE VALUES SHOW STATIONS AND MONTHS IN WHICH WATERS WITH SALINITIES GREATER THAN 35.00 °/₀₀ OCCURRED

Date	113° 30′ E			114°17′ E			114°41′ E			114°53′ E			115°05′ E		
	Depth	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2	*Depth*	*S* °/₀₀	O_2
16/4/48	**278**	**35.25**	**5.76**	**400**	**35.05**	**5.25**	490	34.84	5.70	**260**	**35.02**	**5.51**	**430**	**35.06**	**5.47**
24/8/48	**280**	**35.17**	**5.66**	**410**	**35.11**	**5.90**	525	34.83	5.62	460	34.99	5.93	**460**	**35.09**	**5.91**
11/12/48	275	34.84	5.65	**260**	**35.11**	**5.53**	**310**	**35.06**	**5.57**	476	34.65	5.65	410	34.97	5.60
6/4/49	**320**	**35.06**	**5.90**	300	34.99	5.79	**360**	**35.18**	**5.48**	440	34.93	5.57	**385**	**35.06**	**5.48**
7/6/49	—	—	—	460	34.69	5.75	**380**	**35.00**	**5.60**	**330**	**35.19**	**5.56**	—	—	—
18/7/49	**230**	**35.87**	**5.64**	**260**	**35.25**	**5.86**	**250**	**35.39**	**5.85**	**290**	**35.29**	**5.79**	—	—	—
9/11/49	380	34.65	5.95	430	34.93	5.92	490	34.87	6.01	**410**	**35.05**	**5.87**	460	34.75	5.92
23/2/50	410	34.98	5.76	420	34.75	5.82	440	34.73	5.80	500	34.60	5.80	470	34.65	5.78
21/6/50	**400**	**35.18**	**5.83**	**350**	**35.28**	**5.60**	—	—	—	**220**	**35.84**	**5.37**	**480**	**35.28**	**5.69**
5/10/50	430	34.61	5.32	—	—	—	**430**	**35.02**	**5.72**	**360**	**35.31**	—	—	—	—
18/1/51	290	34.90	5.92	423	34.78	5.92	—	—	—	450	34.81	5.49	**375**	**35.51**	**5.31**
23/2/51	**290**	**35.57**	**6.21**	**380**	**35.00**	**5.48**	520	34.84	5.48	530	34.62	5.52	—	—	—
6/7/51	470	34.74	5.87	500	34.81	5.85	360	34.88	5.91	460	34.80	5.93	**340**	**35.22**	**5.72**

The 27.20 σ_t surface passed through the intermediate salinity min mum (Fig. 2) while the 26.80 σ_t lay at about the depth of maximu variation in total phosphorus (Fig. 4) and of large variations i oxygen saturation (Fig. 3). The 26.80 σ_t surface marked the owe boundary of subtropical waters. These two surfaces were chosen t show the magnitude and characteristics of seasonal changes in inte mediate depth waters off Fremantle.

27.20 σ_t SURFACE

On this surface the salinity-oxygen relationships (Fig. 5) showe that mixing of relatively high salinity, well oxygenated water wit

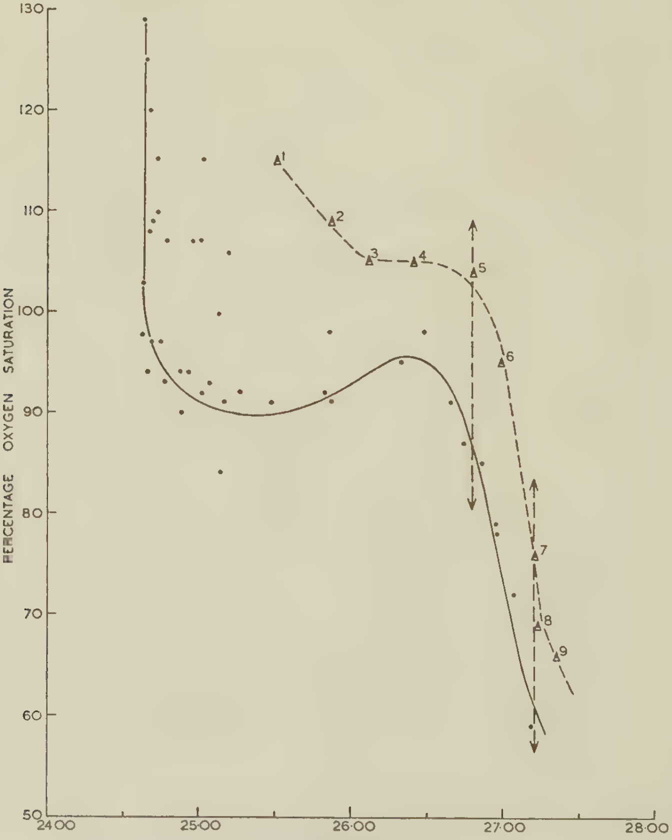


Figure 3. Density (σ_t)-oxygen saturation relationships of waters off Fremantle. Februar 1951.

w salinity, poorly oxygenated water determined the magnitude of ese properties during 1948–1951. Table II shows that the high linity, well oxygenated water occurred between June and October, nerally at depths of 500 m or less. The maximum occurrence of e low salinity, poorly oxygenated water was found in January 51 (Table II) at a depth of 900 m.

6.80 σ_t SURFACE

The salinity-oxygen relationships on this surface (Fig. 6) were riable, partly because of its occasional shallow depth (Table III) ich permitted local surface exchanges to occur; the oxygen superuration on this surface in February 1951 (Fig. 3) certainly indi-

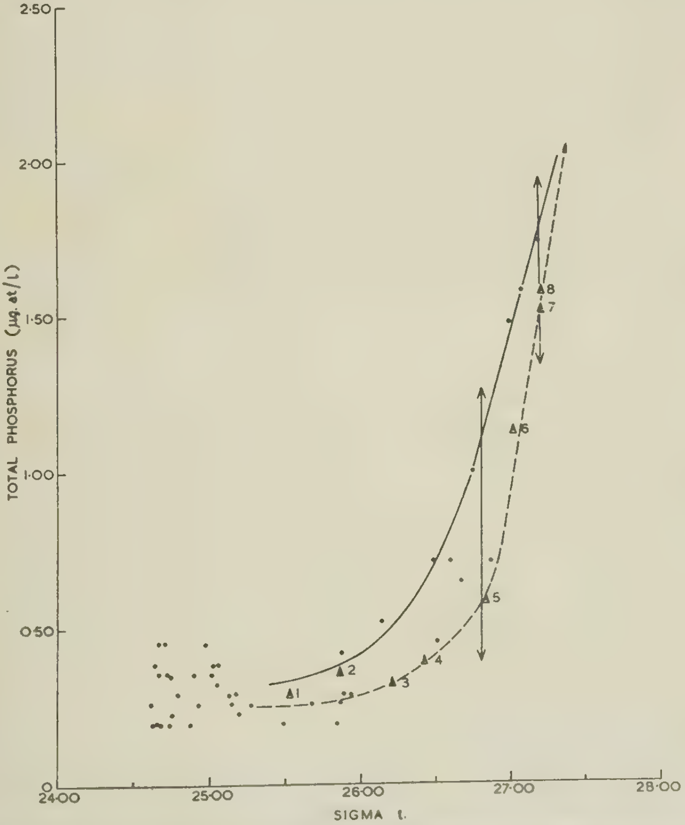


Figure 4. Density (σ_t)-total phosphorus relationships of waters off Fremantle, February 1951.

cated this. Salinities of less than 35.00 $^0/_{00}$ were found at 60 $^0/_0$
the stations between November–February 1948–1950, those great
than 35.00 $^0/_{00}$ at 73 $^0/_0$ of the stations between April–August 194
1951. The magnitude of the oxygen variation was much reduced
this surface compared with the 27.20 σ_t surface.

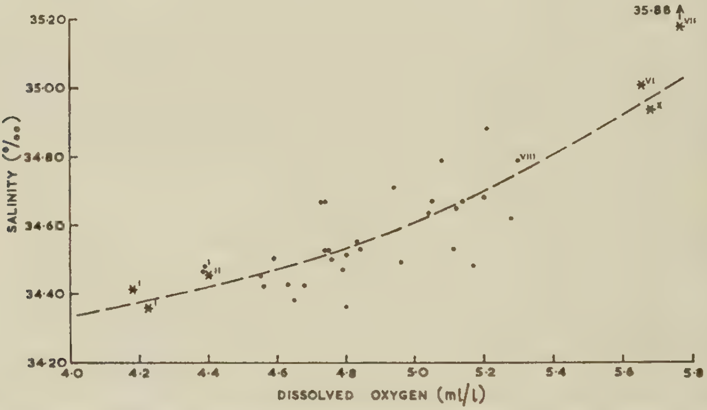


Figure 5. Salinity-oxygen relationships on the 27.20 σ_t surface of waters west of Fremant
during 1948–1951. The asterisk indicates values selected for comparison with Fig. 10.

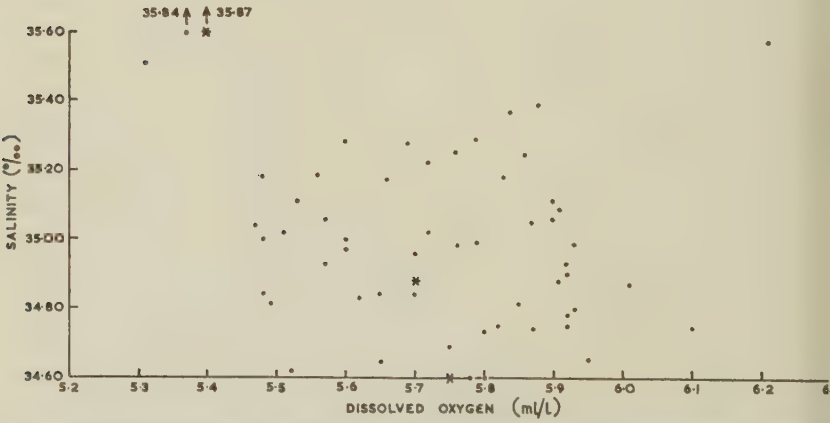


Figure 6. Salinity-oxygen relationships on the 26.80 σ_t surface of waters west of Fremant
during 1948–1951. Asterisk indicates values selected for comparison with Fig. 14.

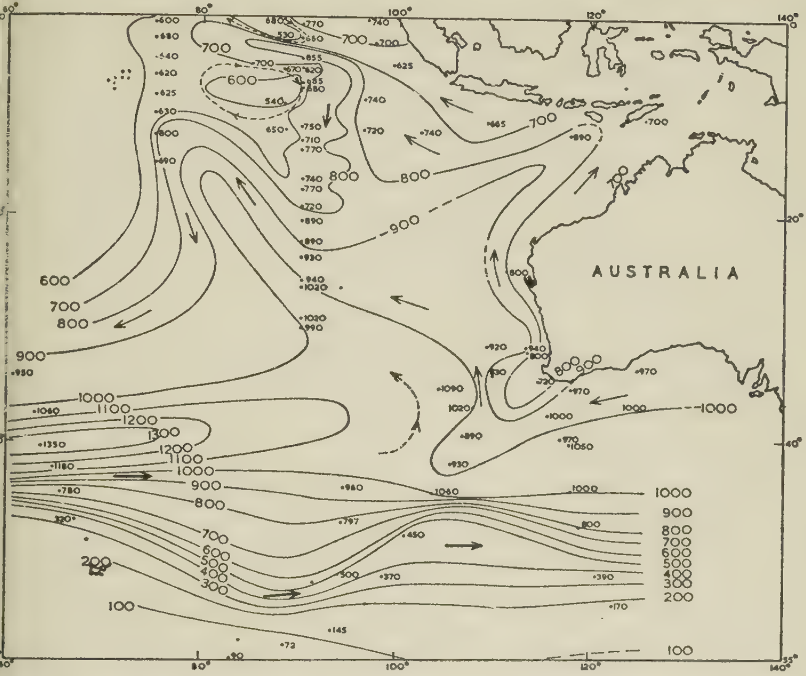


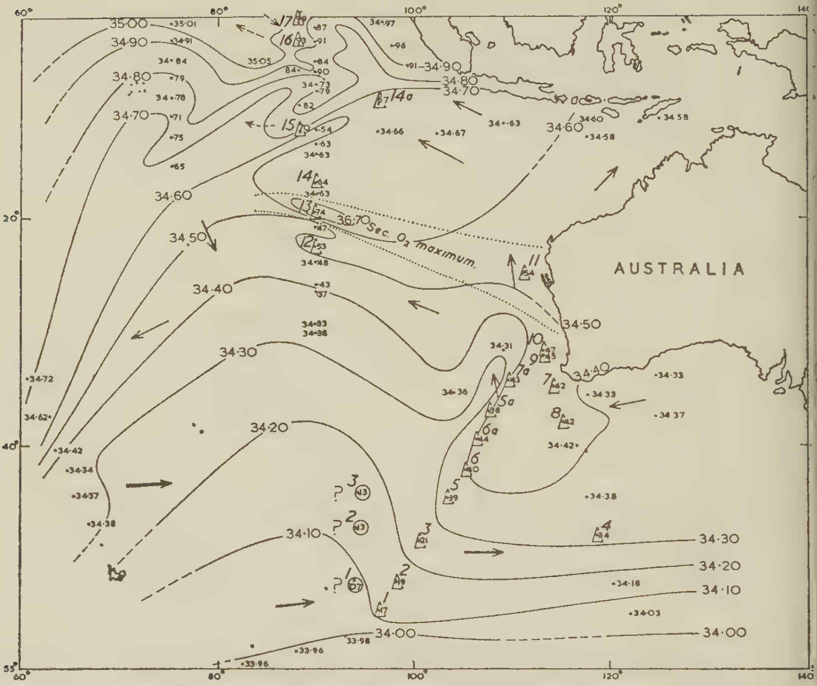
Figure 7. Bathymetry (m) of the 27.20 σ_t surface. Arrows indicate major paths of flow.

CHARACTERISTICS AND BATHYMETRY OF SELECTED SOPYCNAL SURFACES IN THE SOUTHEAST INDIAN OCEAN

Table I shows that the available data were collected during all nonths of the year. To provide sufficient values for contouring, all f the data had to be used, regardless of the month of collection. he scatter in Figs. 5 and 6 shows that the month-to-month changes ff Fremantle can be considerable. It is probable that some of the omplexities in contour pattern described in this section may be due o neglect of such changes.

7.20 σ_t SURFACE

Bathymetry. Fig. 7 shows that there was a strong flow to the east, outh of Lat. 40° S, and that there was an anticlockwise movement round a centre at about 90° E, between 20 and 40° S; several maller gyrals occurred to the north. Zonal flow was general south


60°
80°
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120°
20°
40°
35°
AUSTRALIA
35·00
34·90
34·80
34·70
34·60
34·50
34·40
34·30
34·20
34·10
34·00
36·70 Sec. O₂ maximum
17
16
15
14
14a
13
12
11
10
9
7
7a
8
5a
6a
6
5
4
3
2
1

Figure 8. Distribution of salinity on the 27.20 σ_t surface.

of 40° S and north of about 10° S, with quasimeridional movemen
between.

Salinity. South of Lat. 20° S, low salinity waters were found
the north along the 80° E meridian (Fig. 8). However, the Di
COVERY II data, from which the southernmost contours have bee
determined, are suspect (see *Salinity-Oxygen Relationship* below
hence the extent of these low salinity waters to the south of 40°
may have been much less than is indicated in Fig. 8. High saliniti
on the western side of the region were due to a southerly flow (Fig.
of waters of relatively high salinity from the Equator; low saliniti
on the eastern half of the region between 20 and 40° S must ha
been due in part to the northerly movement (Fig. 7) of low salinit
waters from the south along this side.

Oxygen. Between Lat. 20–40° S the oxygen content of waters
this surface was less on the western than on the eastern side (Fig.

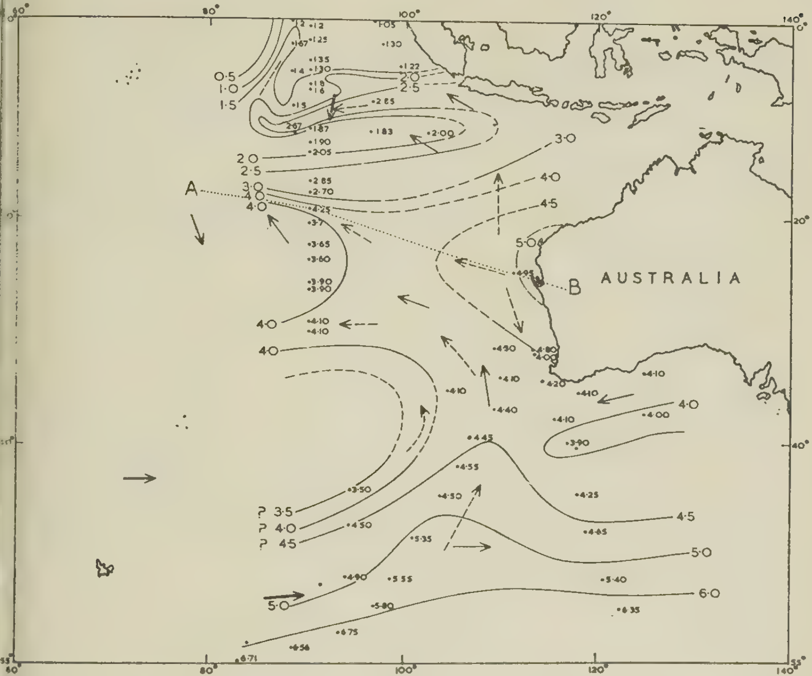


Figure 9. Distribution of oxygen on the 27.20 σ_t surface. Full arrows, showing major aths of flow, are from Fig. 7. Dashed arrows indicate paths of flow of the more oxygenated aters.

he low oxygen values in the region west of 90° E, in about Lat. 5° S, were based on data from Discovery ii Sts. 2701–2703 (Fig. 1); t is possible that these values are too low (see *Salinity-Oxygen Reationship* below) and that no great significance can be attached to hem. North of 20° S the oxygen distribution indicated zonal flow n agreement with previous evidence (Figs. 7 and 8). The Warreen tation off Shark Bay (Fig. 1) showed richer oxygen waters on this urface than elsewhere at the same latitude. Line AB of Fig. 9 indiates the probable centre of zonal movement of these oxygen-rich aters; however, north and south displacement also occurred. orth of 20° S there was a sharp transition from waters of more han 4.0 ml/l oxygen to those of 2.0 ml/l or less.

Salinity-Oxygen Relationships. Fig. 10 shows the extent of oxygen ariations in relation to salinity on the 27.20 σ_t surface. Relative o salinity, oxygen values at points within triangles 10, 11, and 13 were much higher than those for the rest of the data; these poin lay within the secondary oxygen maximum marked on Fig. Also, values at points within circles 1, 2, and 3, from post-w DISCOVERY II Sts. 2701–2703 (Fig. 1), are quite different from t general relationship (Fig. 10, Curve C). It seems probable therefo that the oxygen and/or salinity data from these stations on t 27.20 σ_t surface were in error. The oxygen-salinity relationshi shown by curves A and C in Fig. 10 represent extreme conditio

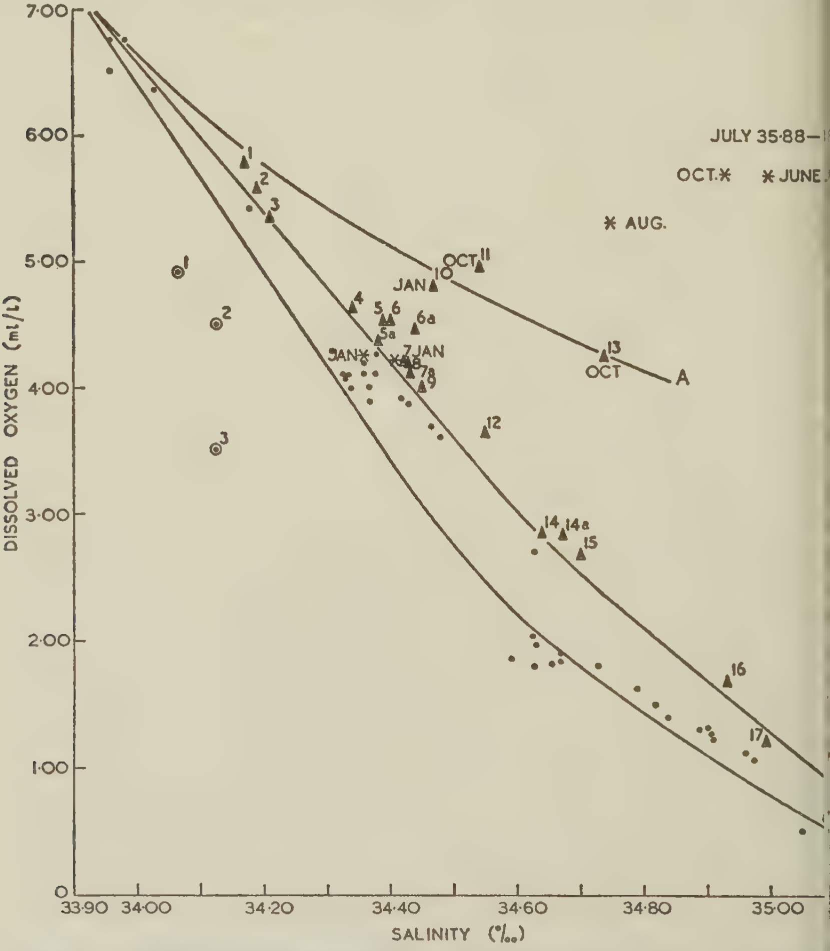


Figure 10. Salinity-oxygen relationships on the 27.20 σ_t surface. Position of values with the numbered triangles and circles are given in Fig. 8. Asterisk values are taken from Fig.

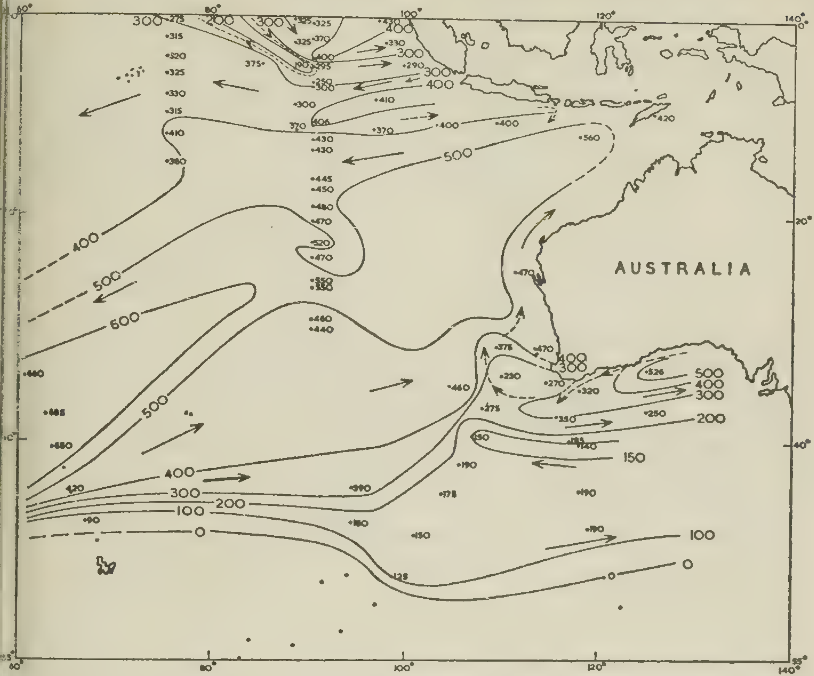
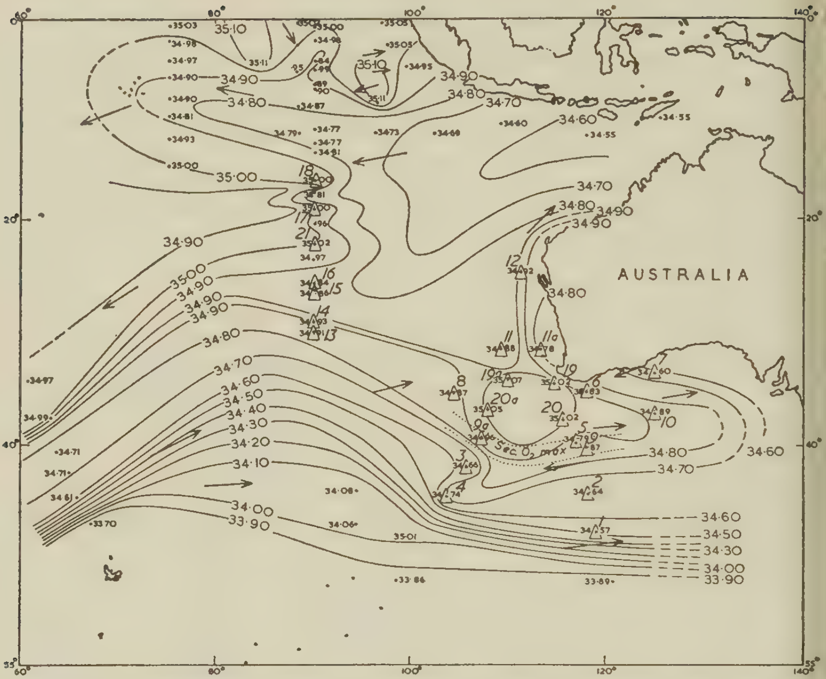


Figure 11. Bathymetry (m) of the 26.80 σ_t surface. Arrows indicate major paths of flow.

f oxygenation of this surface. The data are arbitrarily divided by urve B into two groups; this allows the position of the richer oxygen aters relative to the salinity field to be clearly shown in Fig. 8. n the south such waters had a more southernly distribution (Fig. 8, riangles 5–8) than the oxygen field alone would indicate (Fig. 9). n the northern section the movement of these rich oxygen waters Fig. 8, triangles 16 and 17) towards the Equator was more clearly emonstrated by this means than by the salinity (Fig. 8) or oxygen elds (Fig. 9). The high salinity, well oxygenated waters on this surace off Fremantle (Fig. 10, asterisk values) were not common, lthough values around line A (Fig. 10) were probably derivatives f such waters.

6.80 σ_t SURFACE

Bathymetry. This σ_t surface (Fig. 11) deepened from the surface, t about 45–50° S, to a maximum depth of 500–600 m along a region om about 40° S in the west to 15° S in the extreme east of the


60°
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35·10
35·00
34·90
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34·70
34·60
34·50
34·40
34·30
34·20
34·10
34·00
33·90
35·10
AUSTRALIA
Sec. O2 max
18
17
21
16
15
14
13
12
11
11a
19
19a
20a
20
9a
8
6
7
5
10
3
4
2
1

Figure 12. Distribution of salinity on the 26.80 σ_t surface. Arrows, showing major paths of flow, are from Fig. 11. Values within numbered triangles are referred to in Fig. 14.

area. Northwards from this region this surface decreased in depth to about 200–400 m at the Equator. This bathymetry, which is in general agreement with that of the 27.20 σ_t surface (Fig. 7), shows zonal flow to the east, south of 40° S, and an anticlockwise circulation around the region of maximum depth (Fig. 11). North of about 10° S there was an irregular boundary between eastward and westward movements at about 5° S.

Salinity. Maximum salinity gradients were found south of Lat. 40° S (Fig. 12) at a salinity of about 34.30 $^0/_{00}$. Off the southwest corner of Australia a region of high (near maximum) salinities was found. Between 0–20° S the salinity distribution was governed by the relative amounts of high salinity water from the west and north and by low salinity water from the region between northwest Australia and the Indonesian Archipelago.

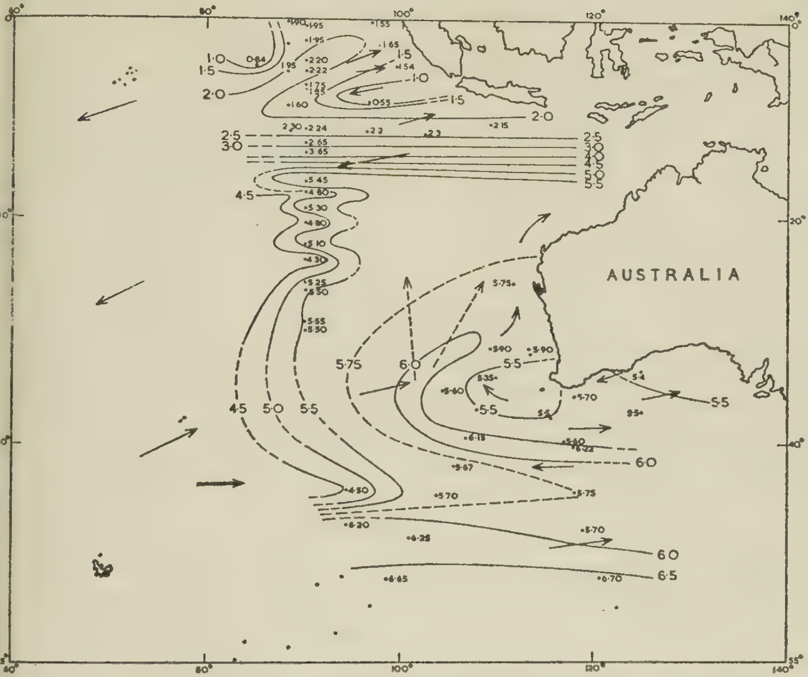


Figure 13. Distribution of oxygen on the 26.80 σ_t surface. Full arrows show major paths of flow (Fig. 11). Dashed arrows show major movements of the more oxygenated waters.

Oxygen. Between 30–40° S the waters on the eastern side were richer in oxygen than those on the western side (Fig. 13). A secondary oxygen maximum on this surface to the southwest of Australia seemed to be the cause of this difference. North of 20° S there was a sharp transition from rich (greater than 4.0 ml/l) to poor (less than 2.0 ml/l) oxygenated waters.

Salinity-Oxygen Relationship. On this surface, oxygen values varied somewhat independently of salinity (Fig. 14). Lines AC and BC indicate that three kinds of water with different salinity-oxygen properties could have mixed around points A, B, and C (Fig. 14) and could have caused these variations in oxygen. Mixtures of A and C have been differentiated (Fig. 12, triangle values) and were found around the region of high salinity off southwest Australia, extending northwestwards to about 20° S and eastwards to the

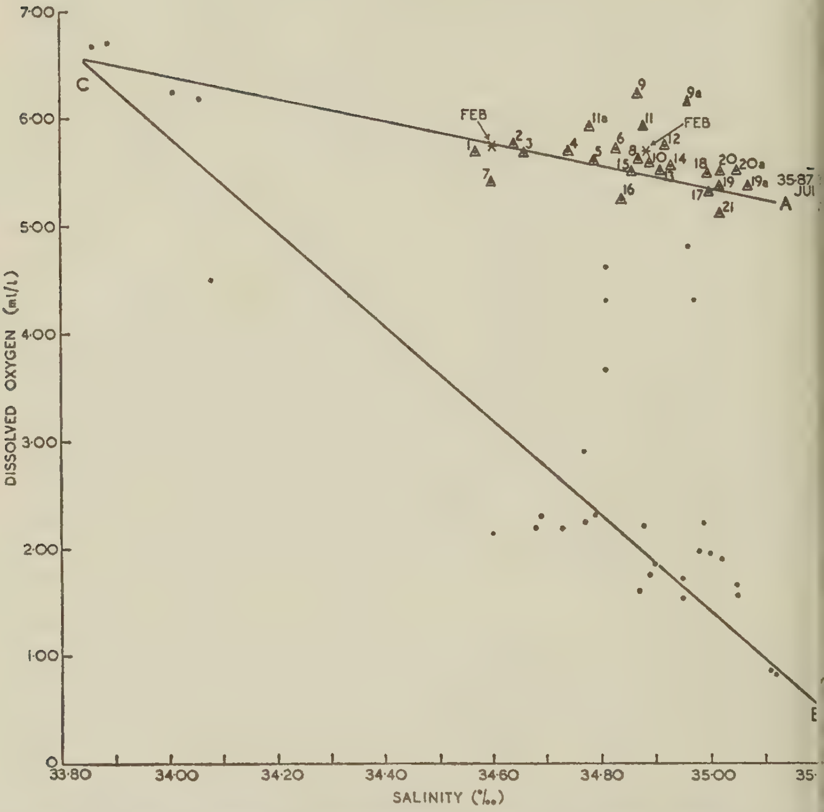


Figure 14. Salinity-oxygen relationships on the 26.80 σ_t surface. Positions of valu within the numbered triangles are given in Fig. 12. Asterisk values are from Fig. 6.

Australian Bight. Mixtures of B and C (Fig. 12, dot values) we found around the Equator and at all latitudes to the west of abo 80° E.

DISCUSSION

Salinity on the 27.20 σ_t surface increased to the north of t region under investigation (Fig. 8). Fig. 15 shows the salinit temperature characteristics of waters along the quasimeridion section (Fig. 1) selected to show the origin of these high salini waters on this surface. Discovery II St. 2683 at the Equator (Fig. had an oxygen content of 1.20 ml/l (Fig. 9) on the 27.20 σ_t surfa

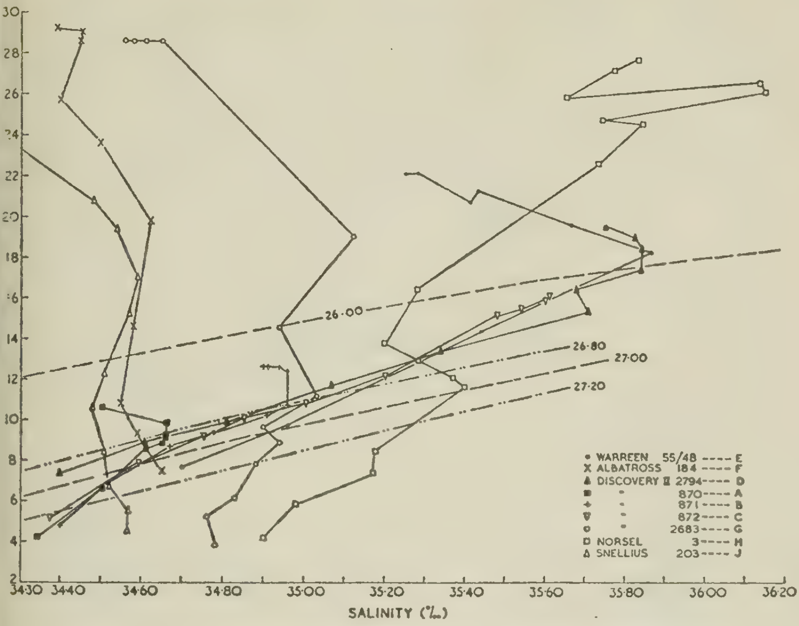
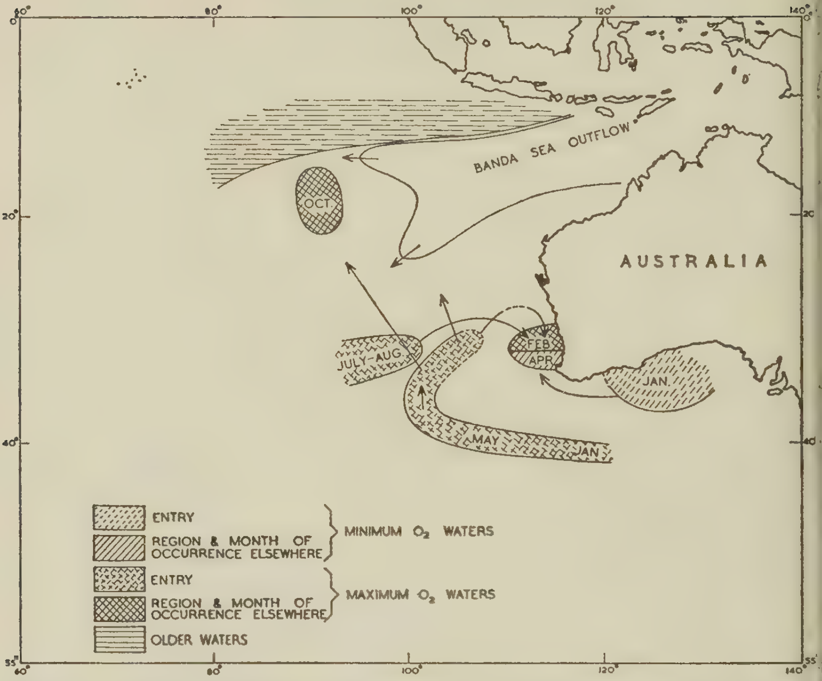


Figure 15. Salinity-temperature relationships of selected stations in Fig. 1.

and a salinity that was nearly intermediate in value between salinities at Norsel St. 3 in the extreme north and at Discovery II St. 870 (Fig. 15) in the extreme south.

It is considered probable, therefore, that salinity and oxygen characteristics of St. 2683 were formed by mixing between waters of the type found at the two extreme stations. The source region of the high salinity intermediate depth water at Norsel St. 3, according to Tchernia (12), is the Arabian Sea. Tschernia also demonstrated the continuity of these Arabian Sea waters southwards of the Equator in the central Indian Ocean. The high salinity waters at the northern limits of the region under investigation will therefore be called Arabian Sea waters.

On the 26.80 σ_t surface, high salinity waters poor in oxygen (Fig. 13) also occurred along the Equator (Fig. 12). These are also considered to be of Arabian Sea origin. However, on this surface, in intermediate latitudes, these were waters with a salinity minimum around 34.50 $^0/_{00}$ in the Banda and Timor Sea regions (Figs. 1 and 15, F and J). Thus the lowering of salinity on this surface was



60°
80°
100°
120°
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20°
40°
55°
BANDA SEA OUTFLOW
OCT.
AUSTRALIA
JULY-AUG.
FEB
APR.
JAN.
MAY
JAN.
ENTRY
REGION & MONTH OF OCCURRENCE ELSEWHERE
MINIMUM O₂ WATERS
ENTRY
REGION & MONTH OF OCCURRENCE ELSEWHERE
MAXIMUM O₂ WATERS
OLDER WATERS

Figure 16. Seasonal movement and distribution of the principal types of water on th 26.80 σ_t surface. Position of convergences from Schott (11).

caused not only by the introduction of upper sub-Antarctic inte mediate waters (Fig. 15, Discovery II St. 870) but by the outflo of low salinity waters from the Banda Sea (Fig. 15, Snellius 203

The dissolved oxygen of waters on the 27.20 and 26.80 σ_t surface decreased rapidly at about Lat. 15° S (Figs. 9 and 13). This regio formed a boundary between waters containing a high proportio of relatively recent surface waters (new) and those with a high pro portion of relatively long isolated subsurface waters (old). Wit 4.0 ml/l as a boundary value, it is shown (Fig. 16) that on th 26.80 σ_t surface the region from 90° to about 130° E, south of 15° S contained new water.

On the 27.20 σ_t surface, a similar distribution of new water wa found, except westwards in Lat. 20–30° S (Fig. 17) and eastward in Lat. 38–40° S into the Australian Bight. However, it is probabl that the reduction in oxygen on this surface in the Australian Bigh

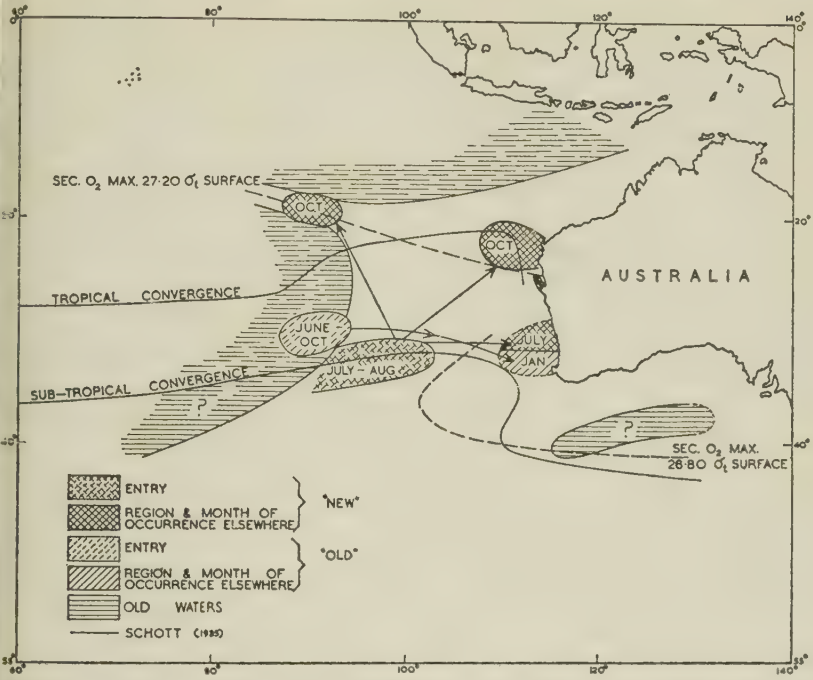
80°
100°
120°
140°
20°
40°
SEC. O_2 MAX. 27·20 σ_t SURFACE
OCT
OCT
TROPICAL CONVERGENCE
AUSTRALIA
JUNE OCT
JULY – AUG
JULY
JAN
SUB-TROPICAL CONVERGENCE
?
?
SEC. O_2 MAX. 26·80 σ_t SURFACE
ENTRY
REGION & MONTH OF OCCURRENCE ELSEWHERE
"NEW"
ENTRY
REGION & MONTH OF OCCURRENCE ELSEWHERE
"OLD"
OLD WATERS
SCHOTT (1935)

Figure 17. Seasonal movement and distribution of the principal types of water on the 27.20 σ_t surface. Position of convergences from Schott (11).

was due to local oxygen demand and that these waters have no continuity with the old waters west of 90° E.

Fig. 4 indicates that new waters would contain less total phosphorus than the old. Upwelling or deep mixing down to 500–750 m in the region dominated by these new waters would enrich the nutrient level of surface waters less than such processes in regions with intermediate depth old waters. This, in part, may be the reason for the reduced nutrient level of the upper 500 m of waters off Fremantle compared with those off Sydney, noted previously by Rochford (10).

Salinities and oxygen values on the 27.20 σ_t surface for waters west of Fremantle were minimal in January 1951 and maximal in July 1949 (Table II). In the former case these waters belonged to the low oxygen group of southeast Indian Ocean waters, and in the latter case to the high oxygen group (Fig. 10).

At a maximum salinity of 35.88 $^0/_{00}$, temperature of 12.5° C would be required at the surface to provide a source region. Schott (11) has shown that the surface salinity maximum around 36 $^{0}/_{00}$ (plat XXVII) has temperatures of this order along its southern limi (plate XXII) in August, in the region 32° S, 100° E. This could b the source region of these high salinity, well oxygenated waters o the 27.20 σ_t surface off Fremantle. On the 26.80 σ_t surface, oxyge values showed that waters of the mixture AC (Fig. 14) occurre during the whole period (Table III). Waters with maximum salinities (greater than 35.00 $^{0}/_{00}$) occurred from February to Septembe only; for the remainder of the year salinity values were much lower However, there was never at any one time a complete dominatio of the region west of Fremantle by either low or high salinity waters The high salinity of 35.87 $^{0}/_{00}$ (Table III) 18/7/49 probably originate from the sinking of high salinity surface waters in the same regio as that suggested for the entry of such waters on the 27.20 σ_t surface. It is considered probable that the major sinking onto th 26.80 σ_t surface occurred to the southwest of Fremantle (Fig. 12 at salinities of about 35.00 $^{0}/_{00}$ and that these waters mixed wit the upper layer of sub-Antarctic intermediate waters to form th lower salinity waters observed off Fremantle. These sources of entr and these possible flow paths have been summarized in Fig. 1 (26.80 σ_t) and Fig. 17 (27.20 σ_t).

CONCLUSIONS

(1) In the southeast Indian Ocean the distribution of salinity an dissolved oxygen on the 27.20 σ_t surface is governed by mixing between the following three types of water:

High salinity (35.00–35.10 $^{0}/_{00}$), poorly oxygenated (0–1 ml/l water of Arabian Sea origin which moves south (east of 80° E) an east (north of 10° S).

Sub-Antarctic intermediate water proper, with a surface salinit of less than 34.00 $^{0}/_{00}$ and an oxygen content greater than 6.0 ml/l which moves strongly to the east, south of Lat. 40° S, but whic has a significant northwards movement to the southwest and wes of southwest Australia.

Water with a salinity greater than 35.00 $^{0}/_{00}$ and an oxyge content of about 5.50–6.00 ml/l which possibly enters the 27.20 σ surface during July–August in the region southwest of Fremant (Fig. 16), whence it apparently flows northeast to Fremantle b uly (Fig. 16) and then north to DISCOVERY II St. 2889 and to WARREEN St. 40/48 off Shark Bay in October.

(2) On the 26.80 σ_t surface in the southeast Indian Ocean the alinity and dissolved oxygen distribution (neglecting surface exhanges) is governed by mixing between the following five types of ater:

Arabian Sea waters, spreading in the same direction as Arabian ea waters on the 27.20 σ_t surface, and having similar oxygen and alinity but higher temperatures.

Sub-Antarctic intermediate waters, with temperature higher than, ut with salinity characteristics similar to, those of the 27.20 σ_t surace, moving east and north along paths similar to those of the 7.20 σ_t surface.

Subtropical water with salinity around 35.00 ‰ and with oxygen content 5.5–6.5 ml/l, entering the 26.80 σ_t surface between uly–August along the subtropical convergence of Schott (11) to he east of 110° E, and moving north and west to arrive at DISCOVERY II Sts. 2889 and 2890 (Fig. 1) in October. Some of this water apparently recurves to the south along the West Australian coast and is found off Fremantle in August.

Water with salinities around 34.60 ‰ (with unknown oxygen characteristics), entering the 26.80 σ_t surface at depths of about 500 m off Timor, moving west along the 10° S parallel, and becoming entrained in the path of the westward flowing subtropical waters at Lat. 15° S.

Water with salinities around 35.80 ‰, sinking along the eastern extremity of the maximum salinity region of the Indian Ocean (Fig. 17), and spreading eastwards.

(3) Off Fremantle, waters with a high proportion of Arabian Sea water are found on the 27.20 σ_t surface in January–February (Fig. 10). For the greater part of the year, however, conditions on this surface are governed by mixing of sub-Antarctic intermediate water with high salinity waters entering this surface to the southwest of Fremantle.

(4) On the 26.80 σ_t surface off Fremantle, only waters of recent sinking in the southwest Australian region occur. Waters of the low oxygen type found to the north of 20° S do not enter the Fremantle region.

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ROWTH AND VARIATION IN SEA URCHINS OF YORK, MAINE[1]

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ABSTRACT

From a three square meter plot of intertidal shore on a rocky point of York, aine, sea urchins (*Strongylocentrotus droebachiensis*) were collected on June 28 and 3, 1957 for study of their size-frequency distribution. Test height, test weight, umber of wedges in the spines, number of pore-pairs in the ambulacral arcs, number of ocular plates insert, and number of coronal plates have been related to test iameter. Evidence indicates that the population probably consists of four year-lasses, with relationships of height and weight to diameter apparently different or each year-class. The mean number of wedges in the spines increases with the ize of the individual. The increase in the number of ambulacral plates is more rapid han that of the interambulacrals. After the urchins have attained about 11 mm test diameter) there is little if any increase in number of ocular plates insert. Be-ween test diameters of 8 and 50 mm there appears to be no significant change in he mean number of pore-pairs per ambulacral arc, which for this population appears o be higher than the figures given by Vasseur (1952) for any of the four Scandinavian ocalities he observed.

INTRODUCTION

Data concerning the characteristics and variations of a species within a limited area of relatively uniform environmental conditions re essential as a basis for the study of variation within that species. One of the most variable species or species complexes among inver-ebrate animals inhabiting the rocky bottom of northern seas is the ea urchin, *Strongylocentrotus droebachiensis* (O. F. Müller), and many ttempts have been made to subdivide this complex. Agassiz (1872–

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1874) stated that he was "unable to distinguish more than one sp cies of *Strongylocentrotus* in the circumpolar specimens thus f collected." There still remain named species whose status is doubte some of which are *S. echinoides* Agassiz and Clark (1907), *S. sach linicus* Döderlein (1906), and *S. pallidus* (Sars) (1871). Mortens (1943: 215–222) has discussed the status of the first two; mo recently Vasseur (1951, 1952) has compared *S. pallidus* with *S. dro bachiensis* and has shown that the extent of differences between th two varies geographically.

The immediate aim of this study is a determination of sever mensurable and meristic characteristics and the extent of the variation within a collection of *S. droebachiensis* taken from a lin ited area on two successive days. Such data may serve as a bas for comparative studies involving geographic variation, habit differences, changes associated with growth, and for possible clar fication of differences between this and related species. Followin such studies, investigation of causes of variation should be possibl Feasibility of such studies is suggested by the fascinating work Shearer, *et al.* (1914) in their hybridization studies with the genu *Echinus* (including what is now known as *Psammechinus*).

Although the present study was carried out on the Atlantic Coas the stimulus was provided at Friday Harbor Laboratories of th University of Washington where students repeatedly asked wheth the light-colored, long-spined sea urchins taken occasionally in th collections were of the same species as the green *S. droebachiensi* It is a pleasure to express appreciation here to Dr. Thomas G. Thom son, who made it possible for the author to spend much time a Friday Harbor Laboratories and to take advantage of their readil available dredging facilities. For his continued interest an encouragement I wish to express appreciation to Dr. G. M. Moore o the Department of Zoology of the University of New Hampshir

METHODS AND COLLECTIONS

The characteristics chosen for study were size-frequency distri ution, height and weight of test, number of plates in the ambulacr and interambulacra, arrangement of apical plates, number of wedge in the spines, and number of pore-pairs in the ambulacral arc These have been related to diameter of test (hereafter referred t mply as diameter), the basic criterion of size, with the aim of monstrating possible differences in these relationships.

For numerous reasons it seemed desirable to obtain the collection om a locality where the population is relatively dense and where e size range of individuals is quite varied. Such a situation was und near the southeast corner of the island on which Nubble ght off Cape Neddick is located (in the township of York, Maine, 43°09′40″ N and 70°35′31″ W). Insofar as possible, all sea ur- ins available in an area 3 × 1 meters were collected during the orning low tides of June 28 and 29, 1957. The greater part of the ea was about one foot below mean low water, but some crevices tended to as much as $1^1/_2$ feet below this. Because of the rough- ess of the bottom and its algal cover, the effective living surface r exceeded three square meters and was greater for small urchins han for large ones.

The most conspicuous algae of the area were the small reds, in- uding encrusting and frondose corallines, and the brown *Alaria sculenta* (L.) Greville. At higher tide levels *Fucus edentatus* De la ylaie dominates. This assortment is characteristic of relatively un- rotected coasts.

About mid-June 1957 some 600 small urchins (< 15 mm in dia- eter) had been collected for study in and around the 3 square eter area sampled two weeks later. Also, we learned subsequently hat each year a considerable number of the large urchins are col- ected from this vicinity for human food. Thus our collection does ot represent an unmodified population. Another factor to be con- idered when attempting a complete collection of any species from n area is the smallest size at which individuals can be detected. lthough very small urchins are nearly white and difficult to see, bout two dozen specimens, ranging from considerably less than mm to about $1^1/_2$ mm, had been taken within a few minutes on une 29, 1953, in the same area. Failure to find a single specimen in his size range in 1957 may well suggest their scarcity.

DENSITY OF POPULATION AND GROWTH RATE

Altogether 1305 whole specimens were collected and dried, the pines removed, and the test diameters measured. No individuals ere found with diameters of less than 3 or more than 57 mm. The pecimens were grouped in 2 mm classes as follows:

2.0– 3.9 — 11
4.0– 5.9 — 74
6.0– 7.9 —133
8.0– 9.9 —138
10.0–11.9 —125
12.0–13.9 — 85
14.0–15.9 — 39

16.0–17.9 — 40
18.0–19.9 — 44
20.0–21.9 — 83
22.0–23.9 — 86
24.0–25.9 —107
26.0–27.9 — 78
28.0–29.9 — 58

30.0–31.9 — 41
32.0–33.9 — 32
34.0–35.9 — 29
36.0–37.9 — 22
38.0–39.9 — 10
40.0–41.9 — 16
42.0–43.9 — 8

44.0–45.9 —
46.0–47.9 —
48.0–49.9 —
50.0–51.9 —
52.0–53.9 —
54.0–55.9 —
56.0–57.9 —

Examination of the size distribution (Fig. 1) indicates fair distinct modes for the 8.0–9.9 and 24.0–25.9 classes and possib modes at 40.0–43.9 and 52.0–53.9 mm. These modes may represe maximum frequencies in year-classes.

From a study of collections dredged in Folden Fjord on the No wegian Coast in July and August of 1923 (Gronlie and Soot-Rye 1925), Grieg (1928) has assumed that the mode at 5–6 mm diamet represents individuals from the previous year's spawning. Althoug the spawning period off Maine varies from year to year and lasts f several months, it generally has its peak in late winter or in t spring (Agassiz, 1864; 1872–74). In the above tabulations it is n clear whether the mode at 8–10 mm represents the modal size individuals that have developed from eggs spawned early in 19 or from spawn of the year before. Before an answer can be foun further data are needed concerning spawning, the time betwee spawning and metamorphosis, and the rate of growth of the sma imagines. When one considers the length of the spawning seaso and the varying growth rate among individuals, the range in siz of this class, from 3 to about 16 mm, is understandable.

That the mode at 24–26 mm represents the next year-class probable. Even though no comparison of the environmental co ditions of the coast of Maine and Folden Fjord has been made, is notable that Grieg (1928) found a strong mode at 23, and althoug he suggests a year-class centered at about 15 mm, his data scarcel support his contention.

As noted, clearly defined modes were not found for the large size This may be due to inadequate sampling or to an increasing ove lap of classes with growth. Whether or not individuals of this speci continue to grow in size as long as they live is still a question. they do not, certainly this method would offer no solution for t determination of groups beyond the cessation of growth.

RELATIONSHIP OF TEST HEIGHT TO DIAMETER

Mean heights (vertical diameter as defined by Clark, 1907: 177) r groups of specimens of limited ranges of diameter are given in able I and Fig. 1. Inspection shows that the plotted points fall nto four groups, each of which makes up a more or less definite raight line. The diameter ranges represented by these lines pproximate 4–15, 17–30, 37–45, and 52–55 mm. If these figures are

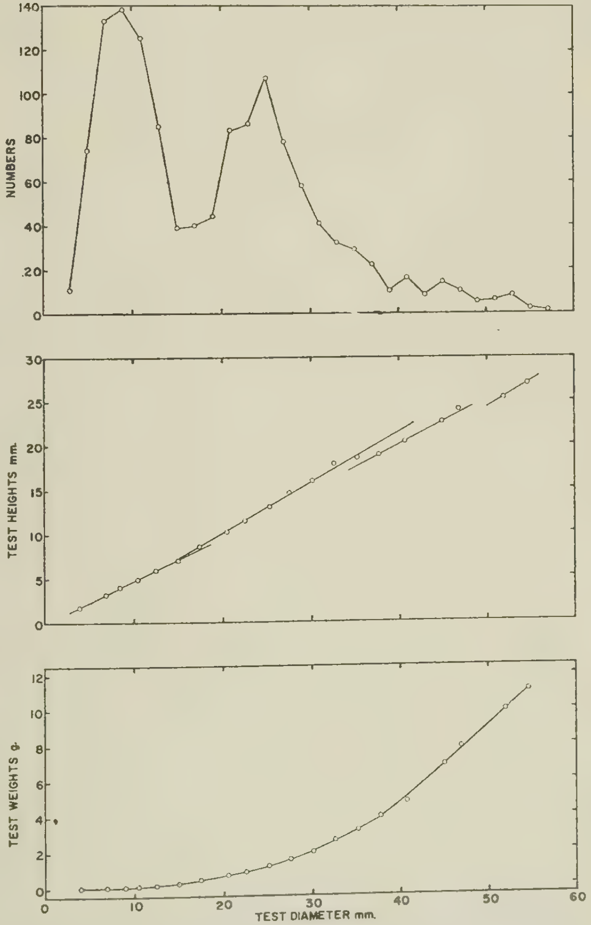

Figure 1. Number of animals, test heights and test weights, of sea urchins from York, Maine, plotted against test diameter.

compared with size-frequency distribution, it is seen that the 8. 9.9 mm mode is not far from the center of the 4–15 mm range, an the 24.0–25.9 mm mode likewise is fairly close to the center of th second line. It appears possible, then, that the lines between 37–4 and between 52–55 mm represent age classes suggested by th poorly defined modes of the 40–44 and 52–54 mm groups referre to in the previous section. If these correlations are justified, the data suggest that each year class in this population has its ow relationship of diameter to height.

NUMBER OF CORONAL PLATES AT DIFFERENT DIAMETERS

The mean number of coronal plates per row—both ambulacr and interambulacral—for groups of specimens of limited ranges diameter are presented in Table I and Fig. 2. These data reve that, at a diameter of 4 mm, individuals of this population hav approximately the same number of ambulacral and interambulacr plates and that ambulacral plates are added more rapidly tha interambulacral plates.

Thus the mean number of ambulacral plates increases progressivel with each size group whereas the interambulacral plates increas less regularly so that at the two largest sizes their number is essentially the same. According to Hsia's (1948) findings, for at least som species of regular echinoids, additional coronal plates are not adde after a certain diameter is attained. Two circumstances, howeve suggest caution before it is concluded that our data support Hsia concept. Our evidence consists of only a single point, with th maximum sizes included here falling far below those recorded fo the species. Also, as noted before, the larger urchins are collecte regularly for food from the sampling locality; it is possible, the that we may be below the potential size maximum for this are

The possibility that the number of ambulacral plates continues t increase beyond that of the interambulacral plates suggests a pattern that is similar to the more strongly marked situation found b Durham (1955: 85–90) for sand dollars. His studies show that, fo at least some of the species, plates cease to be added to the interambulacral areas very early while plates are probably added to th "petals" as long as the animal lives.

Clark (1948: 289) suggested that environmental factors may fect the relationship between the number of coronal plates and the ameter in *S. franciscanus* (A. Agassiz).

ARRANGEMENT OF APICAL PLATES

Although both Jackson (1912) and Vasseur (1952) have suggested at the arrangement of genital and ocular plates varies among pulations and that this variation is related to environmental tors, neither worker has devised a quantitative method for

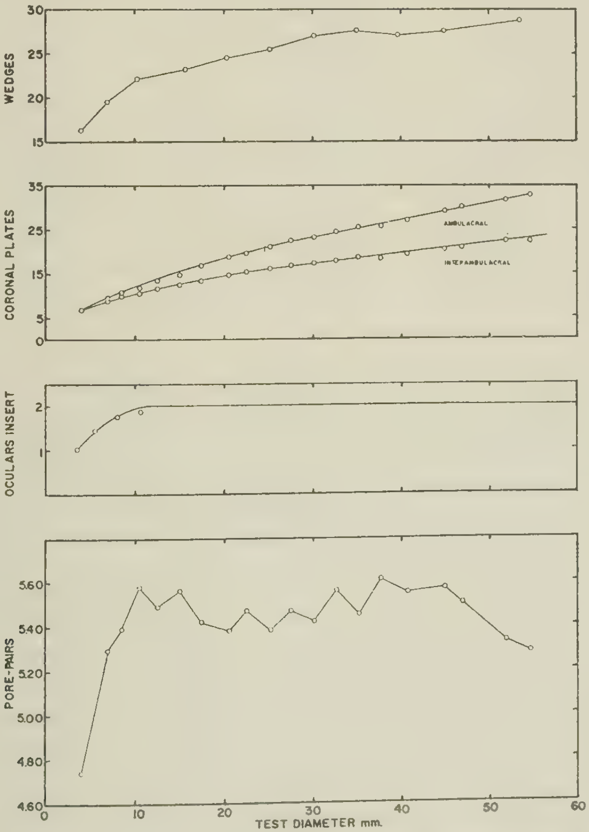

Figure 2. Number of wedges per spine (over-all mean), coronal plates, oculars insert, nd ambulacral pore-pairs per arc at various test diameters.

TABLE I. HEIGHTS, WEIGHTS, AND NUMBER OF CORONAL PLATES A

	Diameters – mm			*Heights – mm*			*Test Weights –*	
No.	*Range*	*Mean*	*C.V.**	*Range*	*Mean*	*C.V.**	*Range*	*Mean*
7	53.2–56.9	54.6	2.6 %	23.4–30.8	27.0	10.9 %	9.6–14.4	11.1
10	50.2–52.9	51.9	1.5	20.9–29.6	25.3	11.7	9.07–11.48	9.87
10	46.0–47.8	46.8	1.5	22.2–25.8	24.0	5.7	6.53–8.79	7.82
10	44.0–45.8	44.9	1.5	19.0–26.2	22.7	9.9	5.31–8.23	6.80
16	40.1–41.8	40.7	1.3	17.5–23.7	20.4	10.7	3.85–5.49	4.75
15	37.1–39.0	37.7	1.5	15.8–23.0	18.8	11.1	3.22–4.79	3.84
20	34.4–35.9	35.2	1.3	16.1–21.5	18.5	6.9	2.78–3.78	3.20
20	31.6–33.5	32.6	1.8	16.1–21.6	17.9	7.8	2.20–3.30	2.66
20	29.0–30.9	30.1	1.9	14.5–17.5	16.0	5.0	1.65–2.42	1.96
20	27.0–27.9	27.5	1.0	13.4–16.2	14.6	4.8	1.29–1.78	1.52
20	24.7–25.5	25.2	1.0	11.9–14.3	13.0	5.2	1.06–1.38	1.20
20	22.0–22.9	22.5	1.6	10.2–12.6	11.5	5.7	.766–1.001	0.859
20	20.0–20.9	20.5	1.6	9.0–11.6	10.2	6.7	.548–.795	0.659
20	17.0–18.0	17.4	2.0	7.1–10.2	8.6	9.7	.308–.563	0.383
18	14.5–15.5	15.0	2.4	6.6–7.7	7.0	4.6	.183–.332	0.236
20	12.0–12.9	12.5	2.3	5.5–6.2	5.9	3.6	.112–.169	0.137
20	10.0–11.0	10.5	2.9	4.5–5.5	4.9	6.1	.0692–.1139	0.0882
20	8.1–8.9	8.5	3.3	3.6–4.4	4.0	5.0	.0418–.0608	0.0502
20	6.0–7.5	6.9	4.8	2.8–3.6	3.2	6.3	.0171–.0376	0.0296
10	3.5–4.5	4.0	8.8	1.6–2.1	1.8	10.6	.0046–.0095	0.0065

* C.V. = coefficient of variation.

expressing the arrangement of these plates. Jackson indicates that 1) the smallest imagines normally have no ocular plates insert (*i. e* all of these plates are exsert or are occluded from the periproct b the abutting bases of the genital plates); 2) at somewhat larger size ocular I becomes insert, and in the vast majority of specimens th characteristic adult arrangement with oculars I and V insert i acquired soon thereafter; 3) some specimens progress beyond thi when more than two oculars become insert—not uncommonly oculars I, V and IV (or I, V and II as a frequent alternate), rathe rarely I, V, IV and II, and very rarely all oculars; 4) among adults arrested development occurs with only ocular I being insert, or i rare cases with none of the oculars insert; 5) in addition to thi regular sequence, occasional specimens have "aberrant" (cf. Jackson) arrangements of these plates. Thus it would appear that th number of oculars insert is one matter and that the number o specimens with aberrant arrangements of these plates is anothe

ASSORTED DIAMETERS FOR SEA URCHINS OF YORK, MAINE

acral Plates		Interambulacral Plates			Pore Pairs/Ambulacral Arc		
Mean	C.V.*	Range	Mean	C.V.*	Range	Mean	σ
32.8	4.4%	21.3–23.9	22.2	4.5%	5.01–5.72	5.28	± 0.32
31.8	4.4	20.9–25.0	22.3	5.6	5.13–5.86	5.33	0.24
30.0	3.5	19.8–22.1	20.9	3.3	5.14–5.90	5.50	0.29
29.0	4.8	18.7–21.7	20.3	4.5	5.02–6.00	5.57	0.32
27.0	3.7	17.9–20.8	19.2	4.1	5.03–5.94	5.55	0.26
25.7	5.9	17.3–20.2	18.6	3.9	5.22–6.21	5.61	0.25
25.6	6.2	17.1–20.2	18.7	4.8	5.02–5.88	5.45	0.29
24.4	4.4	16.8–19.1	17.9	3.7	4.99–5.93	5.56	0.24
23.1	4.2	15.2–19.0	17.3	5.3	5.02–5.86	5.42	0.26
22.4	3.9	15.9–18.1	16.9	3.5	5.01–5.90	5.47	0.29
21.0	3.8	14.8–17.2	16.0	4.1	5.01–5.94	5.38	0.27
19.6	4.9	13.8–16.3	15.3	3.8	5.01–5.92	5.47	0.32
18.9	3.8	13.8–16.6	14.8	4.4	5.00–5.86	5.38	0.25
16.9	7.8	12.4–14.7	13.4	4.6	5.02–5.94	5.42	0.24
14.8	4.7	11.8–13.1	12.5	2.9	5.21–6.00	5.56	0.21
13.5	3.1	11.0–12.5	11.7	3.4	5.01–5.96	5.49	0.26
11.8	4.5	9.9–11.2	10.6	3.4	5.00–5.88	5.58	0.24
10.8	3.9	9.5–10.5	9.9	3.1	5.00–5.93	5.39	0.25
9.5	4.4	8.4–9.5	8.9	3.1	4.90–5.73	5.29	0.23
6.9	7.8	6.1–7.4	6.9	6.1	4.57–4.93	4.74	0.11

In Table II, in addition to a listing of the number of specimens rith their various plate arrangements, the mean number of ocular lates insert and the percentage of aberrant arrangements are given. 1 mm is considered the diameter at which the adult characteristic attained, because nowhere above that size was any continued hange in mean number of plates insert observed. The mean number f ocular plates insert at various diameters is shown in Fig. 2. The ct that the point for specimens between 10.0 and 10.9 mm in iameter falls below the curve suggests that 11.0 mm may actually e slightly too low a figure.

Because of the relatively small number of specimens in some of he small size groups, it seemed desirable to supplement these data. s mentioned earlier, some 600 small individuals had been collected bout mid-June 1957 from the same general location of the 3-meter ollection area. Of the 276 which had been dried, 41 were between 0 and 11 mm in diameter and had a mean number of oculars insert of 1.87. In the diameter range of 4–7 mm there were 198 specimen with a mean number of 1.39 oculars insert. In the other size group there were insufficient specimens for statistical analysis; even so, i should be pointed out that all eight specimens having diameter between 3 and 4 mm had only ocular I insert.

TABLE II. Summary of Data Pertaining to Ocular Plates Insert Amon the Sea Urchins of York, Maine

Test Diameter (mm)	*No. Spec.*	*I*	*I & V*	*A. A.† 2 plates*	*N. & A. A.†† 3 plates*	*Undetermined**	*Mean No.*	*Percent Aberrants*
11–57	881	14	838	I, II — 2 I, IV — 2 V, IV — 2	I, V, IV — 12 I, V, II — 3	8	2.00	1.1
10–10.9	68	9	58	I, IV — 1	0	0	1.87	1.5
7– 9.9	205	51	152	I, IV — 1	I, V, II — 1	0	1.76	1.0
4– 6.9	40	93	43	I, II — 2	0	2	1.33	1.6
3– 3.9	11	10	0	0	0	1	1.0	—

† A. A. = Aberrant Arrangements.

†† N. & A. A. = Normal and Aberrant Arrangements.

* Ocular plates insert are listed as undetermined when: a) the apex of the spec imen was damaged in such a way that the arrangement could not be seen, b) th specimen was not pentamerous, c) apical plates were subdivided in such manne that it was impossible to tell to which plates the insert portions belonged, an d) ocular and genital plates were fused together.

Comparison of all of these data with those compiled by Jackso (1912) indicates that the adult characteristic with respect to ocula plates was reached at a somewhat smaller size in this populatio than in Jackson's series from Dumpling Islands, North Haven Maine. Also, it appears that in this population the average numbe of oculars insert for adult specimens is somewhat above that foun in the Dumpling Islands series. Comparison of Jackson's finding from his study of 2700 specimens from York, Maine, with our dat for the late June collections shows the closeness of our mean numbe of 2.00 oculars insert for 881 specimens with 2.01 for Jackson's 2700

According to Jackson (1912) and Vasseur (1952), some localitie have populations that are characterized by quite different mea numbers of oculars insert. In a later paper Jackson (1914) reporte more marked differences in genera other than *Strongylocentrotu* from waters to the south. Mayr (1954) has noted these later finding f Jackson (1914) but has given no evidence as to whether the dif-erences were genetic or environmentally induced.

TEST WEIGHT

Mean test weights at various diameters are given in Table I and ig. 1. As is often the case when weights are plotted against the ear dimension of an animal or organ, weight increases at an in-reasing rate with increase in linear dimension. Since data of this ype often yield a straight line when plotted logarithmically, such

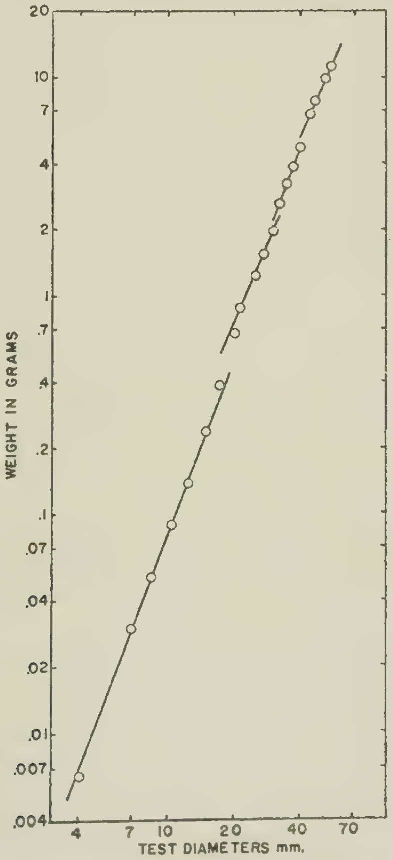

Figure 3. A log-log plot of test weights *vs.* test diameter for sea urchins of York, Maine.

a plot is shown in Fig. 3. Here, however, the result is not a single line but four rather well defined ones; in test diameter ranges these correspond fairly closely with the four lines in the linear plot of test height *vs.* diameter and with the four age classes suggested by the size-frequency distribution. Well defined series of lines rather than a single line have also been observed (Swan, 1952a) in similar plots of weight *vs.* shell length in the clam *Mya arenaria* L.

WEDGES IN THE SPINES

Mortensen (1943), in his diagnosis of species of *Strongylocentrotus*, consistently included the number of wedges per spine. Thus *S. droebachiensis* is generally reported to have primary spines with 18 to 26 wedges. Furthermore, according to Mortensen, Mackintosh (1883) has figured a spine from this species with 31 wedges and Packard (1863) has indicated that in Greenland specimens there are fewer flutings in the spines "from either end of the shell" than in Labrador specimens. For both *S. echinoides* and *S. sachalinicus*, Mortensen has listed the number of wedges per spine as approximately 20. Vasseur (1951) indicated that *S. droebachiensis* has about 24 wedges and *S. pallidus* about 18 per spine.

Gordon (1926) and others have studied the development of the skeleton in various regular sea urchins and have shown that the first spines of the metamorphosed individuals are 6- or 4-radiate; however, little attention has been given to the variation in the number of wedges in the spines from animals of different sizes or from different parts of the same animal.

A beginning has now been made toward filling this gap. Because the spines to be examined had to be removed before a specimen could be studied for other characters, specimens for this phase of study had to be chosen early and without benefit of experience. The chief primary spines of ten specimens from each of eleven arbitrarily chosen size groups were removed from each plate of ambulacral radius 2b and from the ambitus (*i.e.*, around the greatest circumference of the test). These were arranged and stored so that the origin of each spine was known. Later they were broken off and their wedges were counted. Earlier examination of a few specimens (Swan, 1952b) suggested that the spines nearest the peristome generally had the least number of wedges and that the number of wedges per spine averaged less for small animals than for large

es. A summary of the findings is given in Table III. In taking the
erages for row 2b, the five spines nearest the peristome were
parated from those nearest the apex. The spines near the peri-
ome have a much lower number of wedges on an average than the
ines near the apex. For each specimen the mean number of wedges

BLE III. NUMBER OF WEDGES IN SPINES OF SEA URCHINS FROM YORK, MAINE

Diameters (mm)		Mean Number of Wedges			
Range	*Mean**	*Ambital*	*Row 2b, excepting 5 nearest mouth*	*Row 2b, the 5 nearest mouth*	*Over-all*
.3–56.9	53.5	28.2	29.4	17.9	28.8
.8–47.1	44.9	27.1	28.1	16.9	27.6
.5–41.0	39.6	26.4	28.0	16.5	27.2
.8–35.7	35.0	26.8	28.3	15.3	27.6
.0–32.0	30.1	26.1	27.8	14.6	27.0
.4–26.0	25.1	24.3	26.6	14.3	25.5
.0–20.8	20.3	23.2	25.7	14.8	24.5
.6–16.5	15.7	21.3	25.5	13.6	23.2
.0–11.0	10.3	19.7	24.4	13.1	22.1
.0– 7.5	6.9	16.3	22.7	11.9	19.5
.5– 4.5	4.0	12.9	19.5	10.4	16.2

* Each group consists of 10 specimens.

f the ambital spines was averaged with the mean number of wedges
f the spines from row 2b (excluding those from the five spines
earest the peristome). These over-all averages are plotted in Fig. 2.

While the numerical range of wedges per spine in individuals and
groups has not been summarized, in many small specimens the
rimary spines on the plates next to the peristome contained only
wedges. The greatest number of wedges on any single spine was
8; this is far above the usual number for this species and probably
epresented the count on a regenerated spine (Swan, 1952b).

As the size of an animal increases there is an upward trend in
he average number of wedges per spine, with the rate of increase
ecreasing toward maximum size. Because of the low maximum
ize of animals studied, it is not known whether this increase con-
inues throughout an animal's life or ceases at some size below
aximum. The irregularity of the points determined cannot now
e explained, but studies of more specimens with size groupings
aving lower internal range might prove rewarding; the possibility

of irregularities in slope or rate of change in slope relative to ag classes should be examined at the same time.

PORE-PAIRS IN THE AMBULACRAL ARCS

Vasseur tacitly assumed that the mean number of pore-pairs pe arc was independent of the size of an animal after it had six plate per ambulacral row (Vasseur, 1951: 7, 8, table 3). Using Vasseur' system, similar observations were carried out on series of specimen of limited size ranges; the data so obtained are presented in Table and Fig. 2.

In all size groups except those above 50 mm or below 8 mm i diameter, the mean number of pore-pairs per arc falls within ±.1 of 5.50. In view of the fact that the standard deviations of the mean for the individual groups ranged from ±0.21 to ±0.32, it appear unlikely that the fluctuation between groups within the range of diameters considered is significant.

The following facts suggest that the low value obtained for specimens with diameters of only 3.5–4.5 and a mean of 4.0 mm is rea and significantly different from the others:

1. the value of 4.74 is below the next value by five of its standar deviations (±.11 mm);
2. alignment of this value with the next two points suggests consistent trend;
3. in other populations, similar studies show the same sort o situation;
4. the mean number of pore-pairs for specimens of the 10–11 m group, if determined on the basis of the 4th, 5th and 6t plates from the peristome, is only 4.81. This last fact strongl suggests that the plates used in determining the pore-pai number for specimens with only six ambulacral plates per ro are so close to the peristome that they do not have the characteristic number of pore-pairs which the individual acquire at a larger size.

It is not clear that the downward taper in this number at th largest sizes is real, but again alignment of the four groups havin the largest diameters shows a consistent downward trend, and i other populations where similar studies have been begun the sam sort of situation exists.

The frequency of different mean numbers of pore-pairs in 28 pecimens with diameters between 8 and 48 mm is presented as a histogram in Fig. 4. Comparison with Vasseur's (1951, 1952) histograms of comparable data for four Scandinavian localities shows that our population falls more nearly as a normal curve than Vasseur's, with 5.0 close to the low extreme; the Scandinavian localities tend to have a maximum number of individuals with a mean value of 5.0, with more individuals having values above 5.0 than below, possibly excepting the collection from Kristineberg, Sweden. At Tromsø, Norway, where Vasseur obtained his highest values, the arithmetic mean of his plotted values is 5.35 compared to 5.45 at York, Maine. Thus it appears that the number of pore-pairs tends to be higher in Maine specimens than in those of Scandinavia. It is not known whether this is an ecologically induced or selected difference. Mortensen (1943: 205–206) has stated, "The specimens from the Straits of Georgia [between Vancouver Island and the mainland of British Columbia at 49–50° N and connected with the North American side of the Pacific Ocean] appear to have fairly constantly 6 pore-pairs." This might suggest a geographic trend

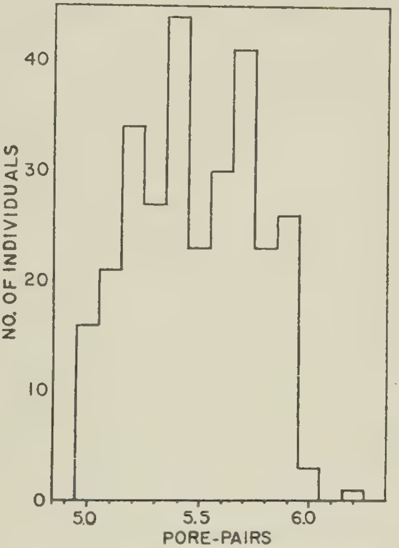

Figure 4. Number of specimens having various mean numbers of ambulacral pore-pairs per arc, based on 289 sea urchins with test diameters between 8 and 48 mm from York, Maine.

from about 5.0 in southern Sweden to higher values northward and westward across the Atlantic and Arctic. Knowledge of the situation on Siberian shores would be of much interest. One should realize that Mortensen did not use Vasseur's system and that even though he recognizes *S. echinoides* as a species separate from *S. droebachiensis*, there is no evidence that he analyzed the distinctions between them to the extent that Vasseur did for *S. droebachiensis* and *S. pallidus*. Thus admixture or confusion may exist. In fact, Swan (1952c), when studying material from just south of the Strait of Georgia, found mean numbers of pore-pairs as follows: 5.40 to 6.63, with a mean of the mean of 5.99 for *S. echinoides*; 5.20 to 5.98, with a mean of the mean of 5.63 for *S. droebachiensis*.

CONCLUSION

The relationships between test diameter and height and weight show four rather distinct series of points. These suggest that each year-class has its own relationships in these respects. At a mean diameter of 4.0 mm, specimens have approximately the same number of interambulacral plates as ambulacral plates, but thereafter the ambulacral plates increase more rapidly than do the interambulacral plates. In this population the characteristic number of ocular plates insert for the adult appears to be attained by the time individuals have reached a diameter of 11 mm or shortly thereafter. The mean number of wedges in primary spines increases at a decreasing rate with increased size of the specimen, and at maximum size (for this sample) it reaches 28.8. The frequency-distribution of numbers of pore-pairs per arc approximates a normal distribution and has its mode at about 5.40. The arithmetic mean for these specimens is 5.45.

For those seeking precedence in the use of other characteristics, reference is made to the papers heretofore cited and especially to the dynamic studies of Moore (1934, 1935, 1937) on *Echinus esculentus* L. The great contributions to our knowledge concerning sea urchins made and brought together by Harvey (1956) and Hyman (1955) should be overlooked by no one planning studies on these animals.

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ON STRUCTURE, ENTRAINMENT, AND TRANSPORT IN ESTUARINE EMBAYMENTS

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ABSTRACT

When fresh water enters the surface of an embayment it moves persistently ward. Enroute it entrains seawater from below to form a halocline, in which salinity increases with depth and to seaward. Wind mixing creates a nearly mogeneous zone in the upper part of the halocline. Below the halocline there is nearly homogeneous lower zone in which sea water intrudes at a rate sufficient supply the demand for entrainment. This fresh water transport system is superposed on the tides which ebb and flood at all depths. There is a surface of no net otion in the halocline above which the net transport is seaward and below which is inwards.

Entrainment is the preferential upward transfer of water from the lower to upper ne. The downward mixing of fresh water is defined by the lower limit of the haloне, which is a surface of unidirectional upward transfer.

The zone structure is accurately defined by plotting salinity as a function of the garithm of depth.

The seaward volume transport through the upper zone and halocline, the in-ard transport through the lower zone, and the upward transfer through the interne boundary may be computed in terms of the continuity of fresh water, where e rate of input is known. Where it is not known, the equations are solved by in-oducing the difference of dynamic height across the embayment. The features of ructure and transport may be defined by application of normal oceanographic data.

This paper is presented in recognition of the inspiration and adership of Thomas G. Thompson.

THE ESTUARY MODEL

In an estuarine embayment the input of fresh water exceeds the sses by evaporation and/or freezing.

From his study of Alberni Inlet (Fig. 1), Tully (1949) concluded at fresh water entering the surface of such an embayment moves rsistently seaward. Enroute it entrains sea water from below to form a halocline in which the salinity increases with depth and t seaward. Usually the upper part of the halocline, mixed to or near to homogeneity by wind, is called the upper zone. Below the hal cline there is a nearly homogeneous lower zone in which sea wat

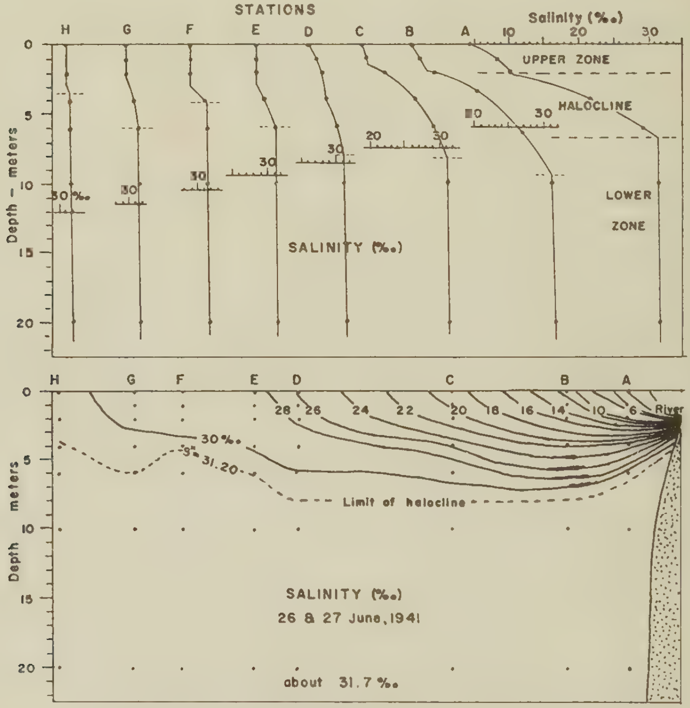

Figure 1. Salinity structure in Alberni Inlet, B.C.

intrudes at a rate sufficient to supply the demands for entrainmen In the steady state (*i. e.*, through a time interval longer than tidal day) the fresh water is displaced (flushed, transported) se ward at the same rate as it enters the embayment. Seawater continuously transferred upward through the halocline along t path of transport. It is mixed with the fresh water and conserv in the upper zone and in the halocline, and it moves seaward at t same rate as the fresh water.

It is of some interest to re-examine the features of this mod in the light of more recent knowledge.

Fresh Water Transport Mechanism. Such a transport mechanism n only recognize the difference in density between the zones. It quires a continuous source of light water (fresh water from pre- itation and land drainage), a continuous source of dense water e ocean), and a sink for the mixed light and dense water (the an).

The greatest concentration of light (fresh) water is at the head the system. Hence there is a gradient of increasing mean density ward. This is compensated by a seaward slope of the sea surface ich is the seaward driving force in the upper zone. The driving e in the lower zone is provided by an opposite slope of the bound- between the zones, downwards towards the head of the system, d by the difference of density between the zones.

It is convenient to retain the terms fresh and saline waters because y indicate continuity with their sources. They can be used inter- angeably with light and dense in the descriptions. Furthermore, most small embayments the heat exchange with the atmosphere uniform over the area, hence the temperature-induced density ructure contributes only to the stability, not to the transport echanism.

The fresh water transport mechanism persists while there is a fference in density between the zones. The entrainment process ntinually reduces this difference. It may be further reduced by dal or wind mixing or by loss of fresh water by evaporation or eezing. If it vanishes, the mechanism fails and the waters become omogeneous. Then some of the homogeneous water may be re- rned to the lower zone of the embayment. Such homogeneity es not normally occur, particularly in embayments where there no region of complete mixing. Usually there is additional inflow fresh water along the route of transport.

Tidal Flushing. Tidal currents flood and ebb at all depths to ansfer the water necessary for the tidal rise and fall. Within the mits of constancy of mean sea level, the flood and ebb excursions e compensating. There is no net transport of sea water. This does t preclude tidal circulation or tidal flushing, since it is not ecessary that the water discharged through a cross-section during e ebb excursion be the same water that entered during the previous ood. The inflow and outflow are usually asymmetric. Hence some art of the tidal volume is renewed during each cycle.

Estuary Mechanism. Usually there are precipitation and lan drainage into a marine embayment. Thus there is zone structur so that both transport and tidal flushing mechanisms occur. In th upper zone the ebb is accelerated and the flood is retarded by th persistent seaward transport. Conversely, the flood is strongest an the ebb is weakest in the lower zone, because of the persistent inward transport. Consequently there is a surface of *No net motio* above which the net transport is seaward and below which it inward (Pritchard, 1952).

In such cases it is difficult to distinguish between the purely tida flushing and the transport mechanism. It is convenient to suppos that the tidal excursions do not contribute to the transport, bu rather that it is due solely to the fresh water mechanism, that occurs as a bias on the tidal excursions, and that it is intermitten with the reversing character of the tides.

The Halocline and Entrainment. Turbulence is a consequence the velocity shear between the upper seaward moving zone an the lower inward moving zone. Turbulence may be regarded as th random exchange of fluid elements. When fluid elements ar exchanged vertically in a stratified fluid their displacement opposed by the stability

$$g\frac{\partial \varrho}{\partial z},$$

where g is gravity, ϱ is density, and z is depth (positive downwards This acts as a restoring force. The elements tend to return to thei original strata. However, having mixed to some extent with surroundings, the densities (salinities) are changed toward intermediat values. Hence they cannot be stable again in their original position In effect they must undergo a series of damped oscillations and com to rest in intermediate positions. Thus a halocline is created, i which there is a gradient of salinity from the lower to upper zone

Entrainment is the preferential upward transfer of lower zon water through the halocline.

It is recognized that fresh water is transferred downward from the upper zone into the halocline. However, if it were transferre below the limit of the halocline, there would be a longitudina gradient of decreasing salinity toward the head of the embaymen in the lower zone. This is not observed. Thus the lower limit of th locline must be the limit of downward transfer of fresh or mixed ter. On the other hand, it is observed that the upper zone and locline become progressively more saline to seaward. Hence there ust be continual upward transfer of sea water through the lower mit of the halocline. It follows that at this boundary the vertical nsfer must be unidirectional, upward.

Above the surface of no net motion the fresh water and entrained water are transported persistantly seaward and are eventually from the embayment. Fresh water mixed downward to or be- w this surface must be retarded or transported toward the head the system. Since it cannot escape from the embayment in these sitions and cannot be dissipated in the lower zone, it must main between the level of no net motion and the limit of the halo- ne and must be preferentially available for entrainment. It fol- ws that the level of no net motion must be in the halocline.

Thus the necessary entrainment and transition of properties from e lower to the upper zone are achieved. The halocline is the zone entrainment. The presence of a halocline is sufficient proof that ntrainment rather than any other process of upward transfer, ch as upwelling (Sverdrup, *et al.*, 1942), is occurring.

Energy of Turbulence. Entrainment depends primarily on the ccurrence of turbulent mixing. This can persist only if there is a ntinuing source of energy. Normally, energy is obtained from the ean flow by the action of turbulent stresses. The intensity of rbulence varies with the energy available in the mean flow, which turn depends on potential energy or head in the upper and lower nes. La Croix and Tully (1954), in their study of Seymour Nar- ws, B.C., showed that about 50 % of the available potential nergy of the tides was dissipated in turbulence. Evidently, at least art of the energy required for turbulent mixing originates with the des. This is effective throughout the depth of tidal action, which usually the whole depth in regions over a continental shelf.

The wind must also be recognized as a source of energy which n lead to turbulent mixing. Eckman (Sverdrup, *et al.*, 1942) owed that the depth (D) of wind influence is

$$D = \frac{6.7\,W}{\sqrt{\sin \Phi}}$$

where W is the wind speed (m/sec) and Φ is the latitude. Within th depth the wind energy is added to the tidal energy, creating furthe turbulence. All evidence shows that the depth (D) of wind mixin coincides closely with the depth of the nearly homogeneous uppe zone. A gradient develops in this layer when the winds are sma (Fig. 1, St. A). In the limit, the halocline becomes continuous fro the lower zone to the surface.

It is at once evident that the lower limit of the halocline must b determined by the mixing forces. If the depth of the estuary i greater than this limit, the halocline and lower zone waters mus be distinct in the structure. This is the case in the deep Britis Columbia inlets observed by Tully and others (Fig. 1). If, howeve the depth of the estuary is less than this limit, the halocline struc ture must reach the bottom. That is, there must be more or les uniform salinity gradient to the bottom. This was observed b Pritchard (1952) and others studying the plains estuaries on th Atlantic coast of United States.

STRUCTURE

Utilization of these concepts depends on definition of the zone which in turn requires an accurate description of the structure. Thi may be accomplished by the method outlined by Tully (1952, 1957 The observed salinity data are plotted as functions of the logarith of depth (Fig. 2). In this presentation the zones are defined, withi small limits of error, by straight lines of constant slope (k) such tha

$$S = k\,ln\frac{z}{z_1} + S_1,$$

where z is depth (positive downwards), z_1 is unit depth, and S_1 i a constant.

The first diagram in Fig. 3 shows such a plot of the salinity dat from Alberni Inlet, corresponding to Fig. 1. The subsequent dia grams show salinity data from Juan de Fuca Strait.

Examination of more than 1000 examples from regions dominate by fresh water showed that this logarithmic plot could be applie with an apparent error of less than 0.1 $^0/_{00}$ in the halocline and o less than 0.05 $^0/_{00}$ in the lower zone in 90 $^0/_0$ of the cases (Tully, 1957

The limits of the zones are defined by the intersections of th lines. According to this interpretation of structure there should b continuities at the upper and lower limits of the halocline (*D* d *L*). These have not been observed and there is some doubt that ey exist. This uncertainty cannot be resolved until adequate strumentation is available to examine the salinity structure in ail. In the meantime these limits are regarded as "virtual" values.

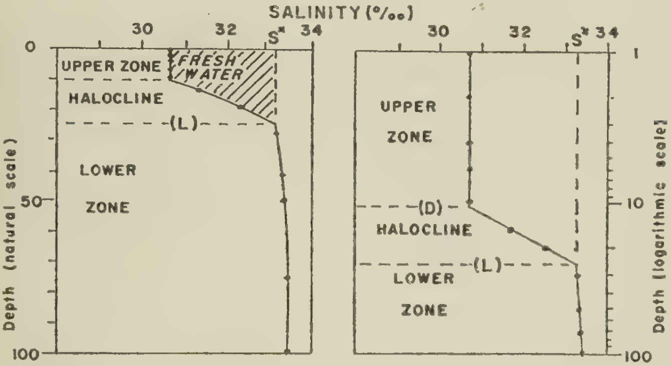

Figure 2. Comparison of natural and logarithmic plots.

The mixing mechanism which creates this structure has not been monstrated. However, it is intuitively apparent that the mechan- n is constant in each zone of constant slope (k). In the halocline is must be the entrainment process.

Index Salinity. The salinity at the lower limit (L) of the halocline fines the water which is about to be entrained. It is called the dex salinity (S^*). This has been found to be remarkably constant any region where the halocline was continuous and where the wer zone water did not change.

Herlinveaux (1959, in preparation), studying Juan de Fuca rait, and Waldichuk (1957), studying the Strait of Georgia, found at it followed an annual cycle associated with the seasonal vari- ion of sea water intruding the lower zone. Tully and Dodimead 957) and Dodimead (1958), working in the eastern sub-Arctic cific Ocean, found it to be constant ($33.8 \pm 0.1\ ^0/_{00}$) both winter d summer during four years (1955–58), despite major changes in e upper zone. From examination of these data it became evident at index salinity is determined solely by the properties and pro- sses in the lower zone. It is independent of the character of the upper zone. This confirms the conclusion that the lower limit (L of the halocline is a surface of unidirectional upward transfer.

Determination of the Fresh Water Fraction (*C*). From the foregoing discussions, the concentration (*C*) of fresh water at an position in the upper zone and halocline is

$$C = \frac{S^*L - \int_0^L s dz}{S^*L}.$$

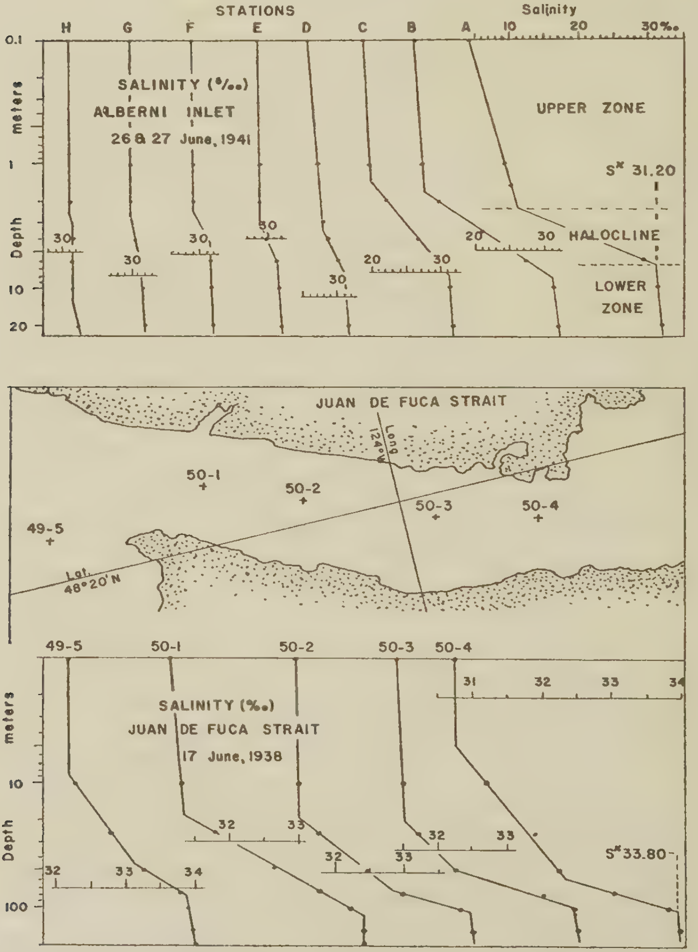

Figure 3. Logarithmic plots of salinity structure in Alberni Inlet and Juan de Fuca Strait, B.C

The relation is difficult to solve in a natural plot because the ructure is often irregular and requires subjective interpretation. lso, the lower limit of the halocline and the index salinity are definite. It is more precise and convenient to first plot the salinity ta as a function of the logarithm of depth, as has been demonrated. Here the index salinity (S^*) and the limits of the halocline and L) can be accurately determined. With this information a ly representative natural plot can be made. Then the numerator obtained readily by planimeter integration of the area between salinity-depth relation and the index salinity. This area is own shaded in the first diagram of Fig. 2. The denominator is area expressed by the product of index salinity (S^*) and the pth of limit (L) of the halocline.

TRANSPORT

Fresh water Equations. It has been established that all fresh water ogether with the entrained sea water is transported seaward through he upper zone and halocline. Then to maintain continuity the fresh ater fraction (C) of the total volume transport through any cross-ection of the upper zone and halocline (T') must equal the rate of nflow of fresh water (Q) from the head to that section. Taking the ositive direction seaward

$$CT' = Q, \tag{1}$$

hence the total transport through the upper zone and halocline is

$$T' = \frac{Q}{C} \tag{2}$$

n units of volume per unit time. Because of the diurnal cycle of he tides it is implied that the unit of time is the tidal day (24 hours, 2.2 minutes) regardless of the units used in calculation.

It is also evident that the seaward transport of the sea water action ($1 - C$) of the upper zone and halocline must equal the upard transport ($-W$) through the interzone boundary in the area etween the section and the head of the embayment. This in turn ust equal the inward transport through the cross-section in the wer zone (T''), else sea water would accumulate or decrease in the mbayment

$$-W = T'' = -(1-C)T' = \frac{1-C}{C}Q. \quad (3$$

It is stipulated in these equations that the zones are defined in th structure (Fig. 2) and that transport is primarily dependent on th fresh water inflow (Q). This is the total of precipitation, river dis charge, and seepage, inwards of the cross-section being considered These quantities vary considerably and are difficult or impossibl to measure accurately. Hence it is necessary to introduce anothe concept to solve the equations.

Transverse Forces. During the flooding tide, the maximum velocit is in the lower zone. In the northern hemisphere these waters mus tend to the right more than those in the upper zone. Hence th greatest depth of lower zone (dense) water must be on the right o the inward flow. Conversely, during the ebbing tide the greates velocity is in the upper zone. These waters must tend to the righ more than those in the lower zone. Thus the greatest depth o upper zone (light) water must be on the right of the seaward flow

In a situation where the flood and ebb flows are opposite, ther must be a cross-channel slope of the isopycnal surfaces, representin the gravity forces required to balance the Coriolis forces which ar associated with the difference of velocity between the upper an lower zones. This is the case in Juan de Fuca Strait, illustrated i Fig. 4. Then

$$\frac{d_2 - d_1}{\Delta y f} = \bar{V}' - \bar{V}'', \quad (4$$

where d_1 and d_2 are the anomalies of dynamic height across th channel, Δy is the width, f is the Coriolis parameter ($2\omega \sin \Phi$), an $\bar{V}'$ and $\bar{V}''$ are the mean velocities in upper and lower zones.

The velocity difference can be related to the transports in

$$\bar{V}' - \bar{V}'' = \frac{T'}{A'} \frac{T''}{A''}, \quad (5$$

where A' and A'' are the cross-sectional areas of the upper and lower zones which can be defined from the structure.

Transport. Combining the concepts it is possible to evaluate the transport.

Substituting for T'' from eq. (3),

$$\frac{d_2-d_1}{\Delta yf} = \frac{T'}{A'} + \frac{1-C}{A''}T',$$

hence the seaward transport in the upper zone is

$$T' = \frac{d_2-d_1}{\Delta yf}\cdot\frac{1}{\dfrac{1}{A'}+\dfrac{1-C}{A''}} \tag{6}$$

d the inward transport in the lower zone is

$$T'' = -\frac{d_2-d_1}{\Delta yf}\cdot\frac{1}{\dfrac{1}{A'(1-C)}+\dfrac{1}{A''}}. \tag{7}$$

In eqs. (6) and (7) all terms on the right side of the equations can e accurately determined in normal oceanographic data.

The application of these equations is demonstrated in a study of uan de Fuca Strait (Tully and Herlinveaux, 1960).

Comments. Cameron (1951) observed the cross channel slope of he isopycnal surfaces in Portland Inlet, B.C. He showed that the ifference of velocity between the upper and lower zones agreed ell with that deduced from direct current observations. Pritchard 1956) made further studies in the James River. He observed that he lateral gradient of pressure is not exactly balanced by the Coriolis orce, as calculated from the observed mean flow. He ascribed the esidual force to the gradient of a lateral Reynold's shear stress. tewart (1957) showed that the discrepancy was probably due to urvature of the flow path.

These studies show that the technique is applicable if care is aken to choose a cross-section in a straight reach of the embayment, r where curvature of the flow path is not a consequence of bound-ry limitations.

In many cases the velocity-depth gradient remains nearly con-tant throughout the cycles of tidal flow, as in Juan de Fuca Strait Fig. 4). In such cases the transverse slope of the isopycnals must emain almost constant. Hence any measurement of the difference f dynamic heights may be utilized, regardless of the stage of the ide during observations. However, in those cases where the velocity radient, and hence the slope of the isopycnals, varies with the tide, t is implied that the mean values through a tidal day should be sed in the equations.

The dynamic heights may be evaluated from any columns in the section which extend to or below the deepest level of the interzone boundary (L). It is unlikely that there would be significant differences of dynamic heights below this level.

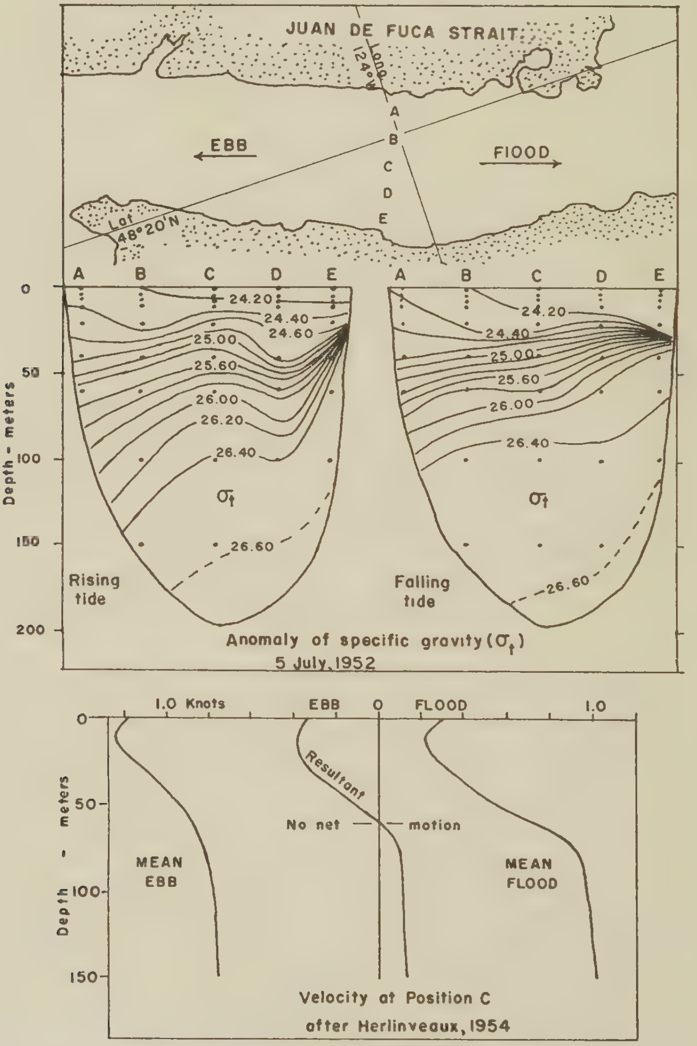

Figure 4. Density and velocity structure in Juan de Fuca Strait, B.C.

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SOME OCEANOGRAPHIC CHARACTERISTICS OF A POLLUTED INLET IN BRITISH COLUMBIA

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ABSTRACT

Physical and chemical characteristics of Neroutsos Inlet, British Columbia, in August 1957 are described. Moderately deep, 11 nautical miles long by 0.5 to 1 mile wide, it has been subjected to a prolonged period of waste disposal from a sulphite pulp mill near its head. The mill effluent is discharged on the surface at the shore and is largely confined to a thin surface layer about 5 m deep. Low dissolved oxygen in surface water was noted and virtual extinction of intertidal flora and fauna within several miles of the mill apparently has occurred. Absence of significant vertical mixing allows the deep water to remain relatively free of contamination. The Inlet lacks the mechanism of a large runoff from the head for rapid flushing of wastes released at the surface.

Comparison of oceanographic data collected in Neroutsos Inlet during August 1927 with those of August 1957 suggests that there has been a long-term change in conditions as a result of 40 years of continuous discharge of mill wastes into Inlet waters.

INTRODUCTION

Neroutsos Inlet is the southeast arm of Quatsino Sound, on the northwest side of Vancouver Island (Fig. 1). It has a northwest-southeast axis parallel to the main trend of the coastline, running from Lat. 50°20′ N to 50°30′ N. Shaped like a typical British Columbia fjord (Pickard, 1956), it is long and narrow with steep mountainous sides. It is 11 nautical miles long, divided into a deep section $7^1/_2$ mi long and 1 mi wide from its mouth to Ker Point and a shallow section $3^1/_2$ mi long and $^1/_2$ mi wide from Ker Point to its head. A cross-section of the Inlet is U-shaped with depths slightly greater than 100 fathoms along midchannel. It has no significant sills, but it is somewhat constricted laterally and vertically at Ker Point, where the effective width is less than 0.3 mi and the depth is only 20 fathoms. In Table I are given some of the morphometric characteristics of the Inlet.

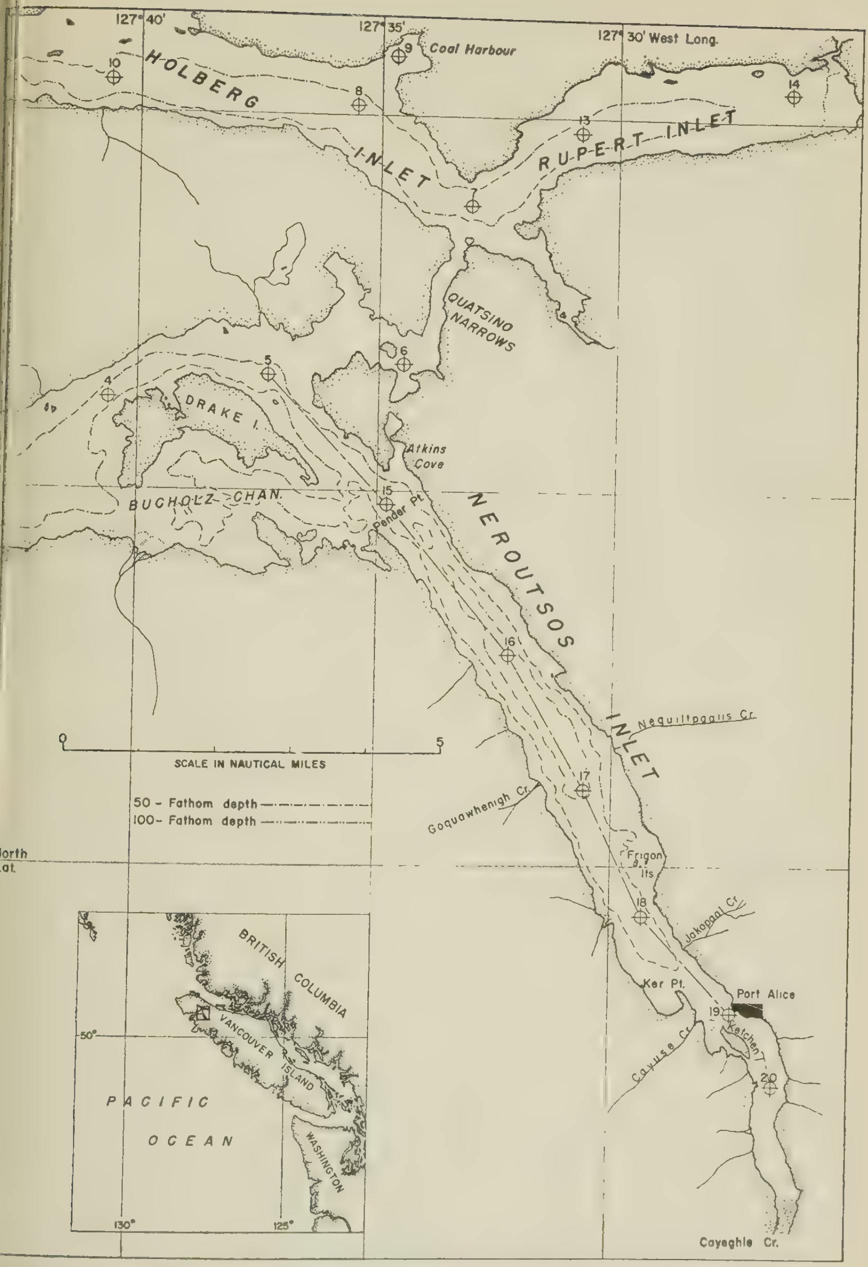
127° 40'
127° 35'
127° 30' West Long.
Coal Harbour
HOLBERG INLET
RUPERT INLET
QUATSINO NARROWS
DRAKE I.
BUCHOLZ CHAN.
Atkins Cove
Pender Pt.
NEROUTSOS INLET
Nequiltpaalis Cr.
Goquawhenigh Cr.
Frigon Its
Jokopaal Cr.
Ker Pt.
Port Alice
Cayuse Cr.
Ketchen I.
Coyeghle Cr.
4
5
6
8
9
10
13
14
15
16
17
18
19
20
0
5
SCALE IN NAUTICAL MILES
50 - Fathom depth
100- Fathom depth
Jorth
.at.
BRITISH COLUMBIA
VANCOUVER ISLAND
PACIFIC OCEAN
WASHINGTON
50°
130°
125°

Figure 1. Chart of Neroutsos Inlet and adjoining waters of Quatsino Sound showing eanographic stations occupied during August 1957. *Inset*: Chart of Vancouver Island turing the general location of Quatsino Sound.

TABLE I. Morphometric Characteristics of Neroutsos Inlet

Dimension	*Common Units*	*Metric Units*
Length from mouth at Pender Pt. to Ker Pt.	7.70 n mi	14.27 km
Length from Ker Pt. to head at Cayeghle Cr.	3.50 n mi	6.49 km
Average width of segment from Pender Pt. to Ker Pt.	0.91 n mi	1.69 km
Average width of segment from Ker Pt. to Cayeghle Cr.	0.47 n mi	0.87 km
Mean depth	48.1 fm	88.0 m
Mean large tidal range	9.5 ft	2.90 m
Mean small tidal range	6.0 ft	1.83 m
Mean tidal prism on large tidal range	0.0140 (n mi)^3	0.0890 km^3
Mean tidal prism on small tidal range	0.00886 (n mi)^3	0.0563 km^3

Horizontal areas:

Depth Contour	*Area*		*Depth Contour*	*Area*	
	(n mi)^2	*km^2*		*(n mi)^2*	*km^2*
Surface*	8.944	30.77	50 fathoms	4.022	13.84
10 fathoms	6.990	24.05	60	3.469	11.93
20	6.285	21.62	75	2.708	9.315
30	5.146	17.70	90	1.822	6.268
40	4.631	15.93	100	1.076	3.702

* Mean high water.

Cross-sectional areas:

Section	*Area*	
	(n mi)^2	*km^2*
From Pender Pt. to point west of Atkins Cove	0.0448	0.1540
From Nequiltpaalis Cr. to Goquawhenigh Cr.	0.0726	0.2495
From Port Alice to Cayuse Cr.	0.00393	0.01348
Across Inlet south of Ketchen Is.	0.00976	0.0335

Volumes:

Depth Interval (fathoms)	*Volume*		*Depth Interval (fathoms)*	*Volume*	
	(n mi)^3	*km^3*		*(n mi)^3*	*km^3*
0–10	0.0761	0.4838	60–70	0.0316	0.2007
10–20	0.0653	0.4153	70–80	0.0267	0.1699
20–30	0.0568	0.3612	80–90	0.0213	0.1353
30–40	0.0483	0.3070	90–100	0.0143	0.0912
40–50	0.0425	0.2706	100–110	0.0055	0.0352
50–60	0.0367	0.2334	Total	0.4251	2.7036

Like most British Columbia inlets, it has a tributary stream at the head. Cayeghle Creek forms a silty delta at the southern end of the Inlet where winter freshets deposit most of the load eroded rom the rugged drainage basin. Its discharge is of the order of 50 cfs .4 m^3/sec) in midsummer, with much greater flows in winter when eavy rains give rise to a large runoff. Numerous streams dissect s margin but they contribute relatively small volumes of fresh ater to the system. Compared to other B.C. inlets, the total olume of fresh water added to Neroutsos Inlet by runoff is small ecause of the confined area of the drainage basin.

The steep slopes bordering this Inlet are heavily wooded. This akes the area attractive for logging, and forest products industries ave been established there from early times.

Meteorological conditions in Neroutsos Inlet are typically those f the west coast of Vancouver Island. Summers are moderately arm and dry, but a large winter rainfall augmented by occasional now gives a mean annual precipitation of 115 inches (292 cm), easured at Port Alice. While the Inlet is sheltered from intense acific storms, it has its own wind regime, which can be quite ntensive at times. Typical of B.C. inlets, there are strong up-inlet inds (northwesterly in this case) on warm sunny afternoons. During nclement weather, winds are southeasterly or down-inlet.

POLLUTION SOURCE

At Port Alice, on the east side of the upper section of the Inlet, sulphite pulp mill has been in operation since 1917. Its production as varied from somewhat modest beginnings through a shutdown eriod of many months during the 30's to about 220 short tons per ay by 1942. Output has continued into 1959 at the latter figure, xcepting a few months of supension of production in 1957–58. In 955, construction was commenced on an expansion of the mill to ncrease production by two thirds to approximately 370 tons per ay (Waldichuk, 1956a).

This mill employs a calcium base in its cooking process, and astes pass untreated into the Inlet. Discharge of effluent, until 957, was by way of a wooden flume. The outfall from which the astes were released was about 15 ft above lower low tide, providing onsiderable mixing of effluent into the surface water. In 1957, a pecially designed flume was installed to allow the effluent to dis-harge into the surface water with a minimum of mixing. The ffluent from the mill has a flow of about 29,000 U.S. gallons per minute (65 cfs, or 1.84 m^3/sec), the water for which is piped from Victoria Lake, located a few miles east of Port Alice.

For every ton of pulp produced, one ton of organic substances that bind the wood fibers together, in addition to about 800 lb of chemicals used in the digestion, are passed into the receiving waters. The main cause of pollution is the high oxygen consumption during decomposition of the organic constituents. With an average of 650 lb of BOD (biochemical oxygen demand) per ton of sulphite pulp (Gehm, 1953: 203), the oxygen demand for a daily output of 220 tons of pulp would be 14.3×10^4 lb (6.49×10^4 kg).

METHODS AND DISTRIBUTION OF PROPERTIES

A survey was conducted in Quatsino Sound August 15–20 with the ship CNAV Ehkoli. Regular oceanographic observations of salinity, temperature, dissolved oxygen and pH were made at stations shown in Fig. 1. In addition, water samples were analyzed for concentration of spent sulphite liquor (SSL). Water samples were taken with a bucket from the surface and with Nansen sampling bottles from depths of 1.8, 4.6, 9.1, 13.7, 18.3, 27.4, 45.7, 91.4, and 137.2 m (6, 15, 30, 45, 60, 90, 150, 300, and 450 ft) or from as many of these levels as the depth of water would allow.

Samples for salinity were taken in 8-oz (237 ml) medicine bottles that were corked securely and waxed to prevent evaporation. Titration for salinity was carried out at the base laboratory by the standard Mohr method.

Dissolved oxygen samples were drawn into 300-ml BOD bottles and treated for titration immediately on board ship. The standard Winkler procedure set up in a shipboard oxygen titration kit was used. The kit allowed 100-ml aliquots of treated sample to be drawn with an automatic pipette attached to a vacuum system, and agitation during titration was effected with a magnetic stirrer. Standardization of sodium thiosulphate was carried out with a standard solution of 0.01 N potassium bi-iodate.

Hydrogen-ion concentration was determined on shipboard using a Beckman pH meter (Model H-2, 110 volts a.c.). All samples were brought to laboratory temperature in a water bath and the pH readings observed were corrected for temperature of the water samples *in situ*.

Concentrations of spent sulphite liquor were determined at the ase laboratory on the samples used for salinity titration. Samples 50 ml were treated according to the method described by Pearl nd Benson (1940). A Beckman DU Spectrophotometer set at 410 mμ avelength was used for absorption measurements. Undiluted diges-r liquor from the pulp mill was used as the standard; concen-ations of SSL in the water samples are given as parts of the diges-r liquor per million parts of water (ppm). Naturally occurring nin-like substances in inshore sea waters contribute apparent L concentrations of the order of 5 ppm. Hence, it is considered at any values lower than 10 ppm are insignificant insofar as con-ibution from the pulp mill is concerned.

Distributions of conservative properties, shown in Fig. 2, are pical of a stratified inlet. The salinity distribution indicates a latively high salt content, almost 33 $^0/_{00}$, in the deep water; com-ared to the deep water in Alberni Inlet (Waldichuk, 1956b), this about 0.5 $^0/_{00}$ higher. The surface water exhibits moderately low alinities, which are confined primarily to the head of the Inlet. marked salinity stratification in the upper 5 m is apparent near he head where salinity ranges from 13 to 25 $^0/_{00}$ in a shallow sur-ace layer. Variation of salinity with depth is less obvious near the outh where the range is only 2.5 $^0/_{00}$, from 30.5 $^0/_{00}$ at the surface o 33.0 $^0/_{00}$ near bottom.

Temperatures observed during the survey showed the effect of urface warming of the water. The vertical gradient found at the ead of the Inlet (surface 17°, bottom 8° C) diminishes seaward and s markedly less at the mouth of the Inlet (surface 15°, bottom 8° C). certain amount of mixing evidently takes place near the mouth hich partially destroys thermal or salinity stratification set up ocally. Tidal movement from the relatively well-mixed areas of uatsino Sound brings water into Neroutsos Inlet which is more omogeneous than that formed therein.

The density (σ_t) distribution exhibits the large range resulting rom salinity and temperature gradients, both tending at this time o make the surface water light and the deep water dense. A large ange in σ_t from 8.5 at the surface to 23 at a depth of 10 m in the pper 10 m near the head of the Inlet exemplifies the great stability f this surface layer.

The nonconservative properties (Fig. 3), especially dissolved xygen concentration, exhibited distributions which were unusual

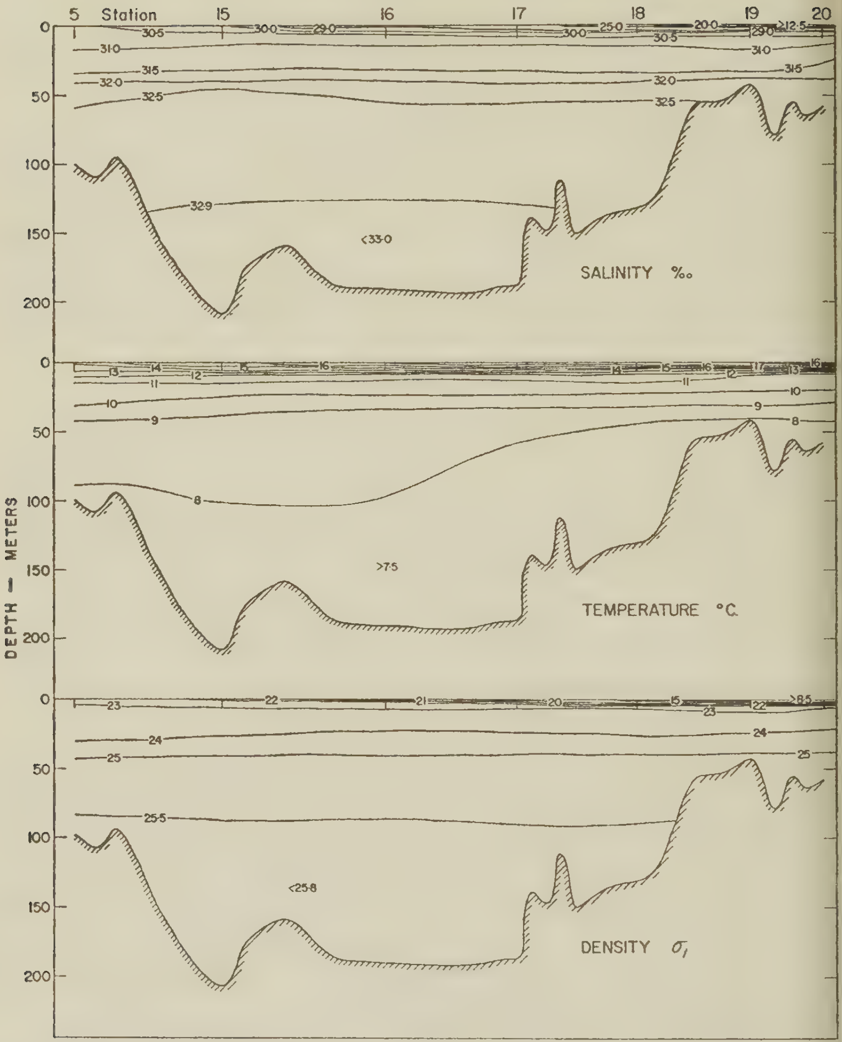

Figure 2. Distributions of salinity, temperature, and density (σ_t) in longitudinal sections through Neroutsos Inlet, August 1957.

for a normal inlet but which are probably typical for one receiving wastes from a sulphite pulp mill. Surface dissolved oxygen concen- trations in the upper part of Neroutsos Inlet, within a radius of a mile of the mill, were as low as 0.16 mg-at/l; up to 2 mi north and

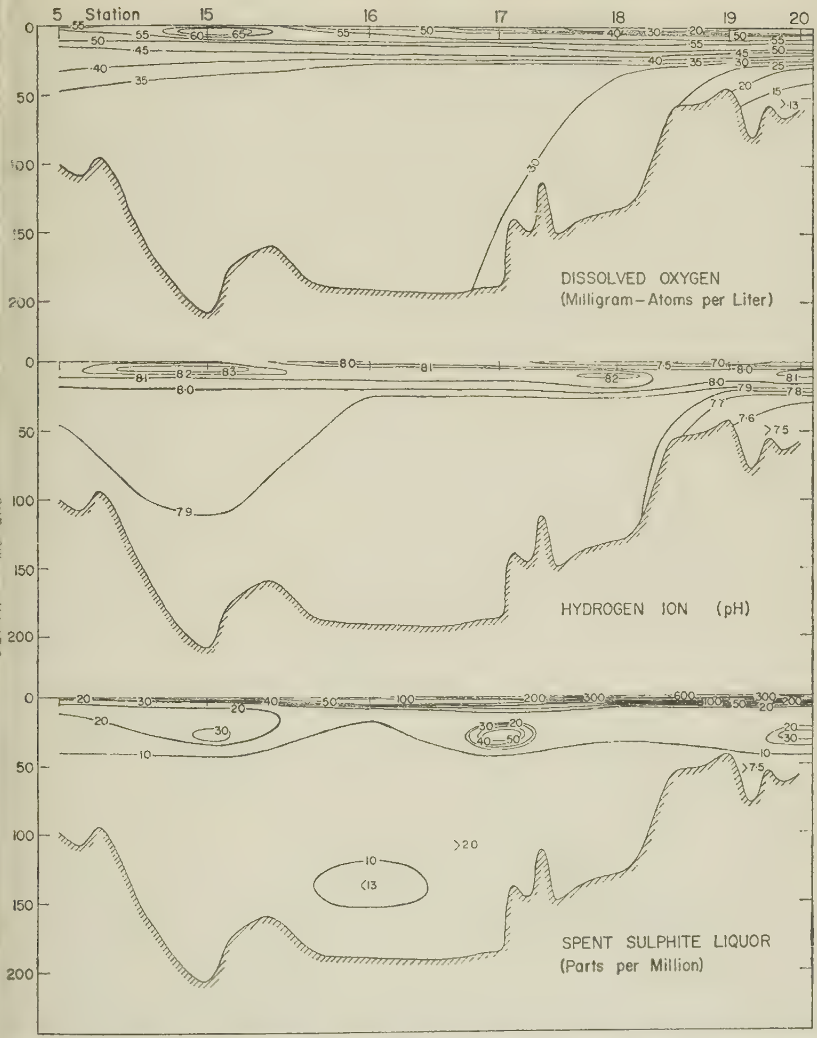

Figure 3. Distributions of dissolved oxygen, pH, and spent sulphite liquor in longitudinal ections through Neroutsos Inlet, August 1957.

outh of the pulp mill they were less than 0.3 mg-at/l. This layer f low dissolved oxygen was relatively shallow, less than 5 m deep. elow the surface layer, concentrations of dissolved oxygen rapidly ncreased to a maximum, greater than 0.55 mg-at/l at a depth of about 10 m. Whether this high oxygen content resulted from "fresh" sea water moving up the Inlet under the seaward-moving surface layer or from high local photosynthetic activity is uncertain, but the latter cause is suspected. Below this high oxygen zone there was a decrease in dissolved oxygen until concentrations as low as 0.15 mg-at/l were reached in the bottom water at the head of the Inlet. Low oxygen concentrations in this part may be partially due to decomposition of organic substances released from the mill. However, it is probable that low dissolved oxygen is a natural consequence of horizontal and vertical constriction of the Inlet near Port Alice and of a lack of vertical flushing behind the sill.

Dissolved oxygen concentrations in the lower part of the Inlet were typical of ventilated British Columbia inlets. A moderately high dissolved oxygen concentration at the surface increased to supersaturation in a zone at about 5 m depth where vigorous photosynthesis was apparently occurring. In the deep water there was a gradual decline in the amount of dissolved oxygen down to the bottom, where concentrations were just over .30 mg-at/l.

The distribution of pH was closely parallel to the distribution of dissolved oxygen, but variations of pH were not as large. Except for the area in the vicinity of the mill, where surface pH was just under 7.0, the sea water exhibited a high of about 8.0 at the surface and a low of 7.6 at depth. The region of oxygen supersaturation near the surface at St. 15 was characterized also by a high pH, greater than 8.3. Deep water in the upper Inlet showed a relatively acidic state with a pH of less than 7.6, but that in the lower Inlet was comparatively alkaline, 7.8 to 7.9.

Spent sulphite liquor in high concentrations of over 200 ppm was confined to a thin surface layer of less than 5 m thickness. These concentrations extended for about 2 mi north and 1 mi south of Port Alice. There was a rapid decrease of SSL with depth in all parts of the Inlet. Cells of relatively high concentration of SSL found at intermediate depths suggest that there was occasional mixing of effluent with deep water either through wind or tidal action. Concentrations of less than 10 ppm shown in the deep water may be unrelated to the pulp mill waste since they could be caused by naturally occurring lignin-like substances in sea water.

OTHER OBSERVATIONS

Color of the water was a reddish brown from the head of the Inlet o about 5 mi below the mill. As measured with a Secchi disc, the epth of visibility increased from about 2 m in midchannel opposite e mill to 5 m at a distance of 6 mi from the mill, to 6 m at the outh of the Inlet and to 7 m at the entrance to Quatsino Sound. ccording to reports from aqualung divers, visibility in the water Port Alice Harbor is poor to a depth of 4 or 5 m; below this depth, en adjacent to the mill, the water is generally clear and visibility good, with sufficient light penetrating through the dark upper yer to allow moderate illumination.

A considerable amount of foam was observed in the Inlet, particularly on windy days. The densest foam was in the immediate icinity of the outfall, but wind-stirring produced streaks of foam paralleling the direction of the wind for considerable distances down he Inlet. Presence of foam is a direct consequence of the presence of SSL, which has a low surface tension and tends to froth when erated by stirring.

While no quantitative biological sampling was carried out, some ncidental observations of fish, intertidal fauna, and vegetation were made. For a mile north and south of Port Alice on both sides of the Inlet, no evidence could be found of intertidal plant or animal ife, excepting a greyish-green fungus slime, possibly *Sphaerotilus*, which is characteristic of pollution from SSL (Neale, 1958). The cobbles, sand, and other shore materials were plated with a glossy, pitch-like substance. Presence of molluscan shells in the intertidal zone suggests that intertidal animals were common at one time. The pilings of the docks and other waterfront structures at Port Alice were remarkably free of any fouling organisms. It has been remarked by local residents that a good way to remove fouling from boats is to tie up at the mill's wharf for a few days.

While night observations in the presence of a deck lamp secured on the ship usually provided an opportunity to observe a large number of small fish swimming into the illuminated area around the ship, no fish, large or small, were observed at a 30-hour anchor station in Port Alice Harbor. Only two jellyfish were noted drifting past the ship during daylight observations.

About 1.5 mi north of Port Alice, at Jakopaal Creek, particularly where flushing by fresh water occurs, a few barnacles and some seaweed were noted on the rocks. At the head of Neroutsos Inlet, where Cayeghle Creek enters over the tide flats, 2.5 mi south of Port Alice, occasional small mussels in addition to sparsely populated barnacles on old pilings were found. On the shores around Frigon Island, 2.3 mi north of Port Alice, a more normal distribution of plant and animal life than that to the south was found. Sea weed was present in great profusion on the rocks, barnacles in fairly large concentrations encrusted shore materials of the intertidal zone, and the water in this region was considerably clearer than that found only a mile to the south.

CHANGE IN OCEANOGRAPHIC CONDITIONS OF NEROUTSOS INLET FROM 1927 TO 1957

The first oceanographic observations conducted in Neroutsos Inlet to note the effects of the Port Alice pulp mill were made on 17 August 1927 by Hutchinson and Lucas (1927) on the CGS MALASPINA of the Federal Fisheries Department. This was 10 years after commencement of pulp production at Port Alice and exactly 30 years prior to the August 1957 survey. The 1927 observations were initiated in consequence of complaints of alleged harmful effects of the wastes from the mill upon the fishing industry.

Five stations were occupied at distances of 0.01, 1.25, 3.5, 7.5 and 15 n mi seaward from the mill. Distributions of salinity and temperature in deep water were not especially different from those observed in 1957. However, in the upper 10 m, salinities were greater by 1 $^0/_{00}$ in 1927 than in 1957. At the head of the Inlet, the difference in surface salinity was more than 10 $^0/_{00}$, the lower salinity occurring in 1957. Temperatures in the upper 5 m were also higher by 1 to 4° C during the 1957 survey.

Dissolved oxygen concentrations observed during August 1927 and August 1957 were significantly different, especially in the surface layer. In Fig. 4, profiles of vertical oxygen distribution for the stations occupied in 1927 are compared to those 1957 stations located nearest to them. There were low dissolved oxygen concentrations at the surface at stations near the pulp mill in 1957; these were not apparent in 1927. At 10 m, the oxygen concentrations were considerably higher at all stations in 1957 than in 1927. The total amount of dissolved oxygen between 10 m and the surface was greater in 1957 than in 1927 at the two seaward stations only

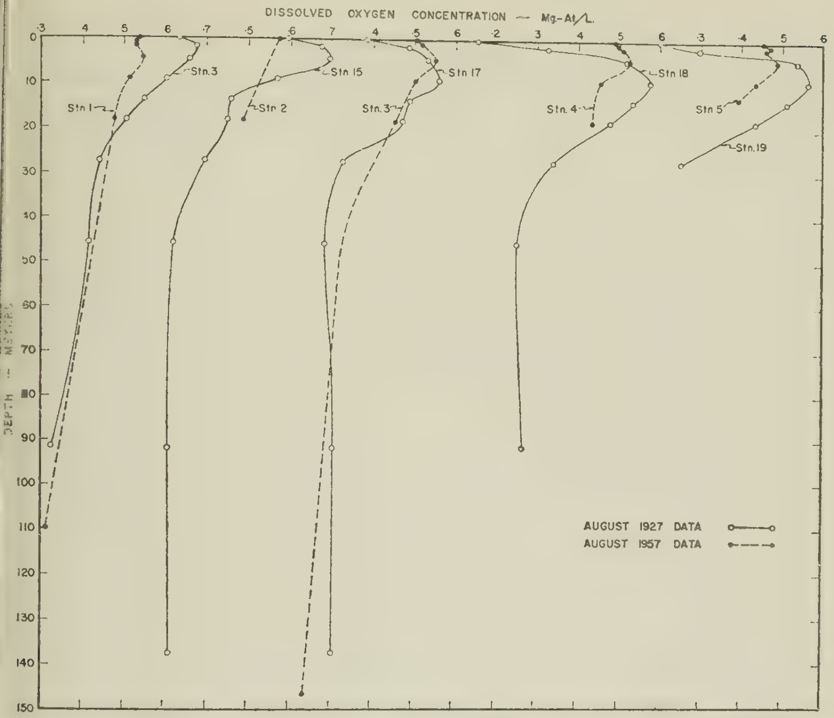

Figure 4. Profiles of dissolved oxygen distribution at stations of comparable location in Quatsino Sound during August 1927 and August 1957.

(Sts. 3 and 15 for 1957; Sts. 1 and 2 for 1927). From the available data, the dissolved oxygen concentrations in deep water appeared to be about the same during both survey periods.

Plankton observations carried out in 1927 showed the presence of various forms of phytoplankton and zooplankton which are expected normally in sea water during the season when samples were taken. It was stated by the authors that plankton organisms were not found in the immense quantities which characterize areas where pilchard were abundant. The fishery guardian reported, at the time, that salmon were being caught in Neroutsos Inlet as formerly. Herring were abundant and spawned in the Inlet during the season prior to August 1927; some dead herring were found on shore, but the cause of death was not known. A pilchard "run" to the head of

Neroutsos Inlet had occurred in 1925 but had not recurred in 1926 or in 1927 prior to the time of the survey.

Hutchinson and Lucas (1927) concluded "that the chemical and physical properties of the water in South East Arm, Quatsino Sound, were well within the limits of sea waters of the continental shelf at the time of this investigation."

DISCUSSION

The low dissolved oxygen concentrations found in the surface waters of Neroutsos Inlet appear to be a direct result of the spent sulphite liquor discharged from the Port Alice pulp mill. The weather prior to the 1957 survey was probably such as to accentuate pollution characteristics in the surface water. That is, a period of abnormal precipitation and runoff was followed by calm warm weather that allowed stratification of surface water to take place with little mixing of effluent into deep water. High surface temperatures promoted decomposition of the mill wastes. Conditions observed at this time were probably the worst for the year, and it is likely that dissolved oxygen concentrations are near normal in the surface water during autumn and winter periods when wind mixing is common.

Because of the geography of Neroutsos Inlet, the dispersion of industrial wastes is confined to essentially one dimension, along the axis of the Inlet. In this respect, an inlet is probably the marine feature most comparable to a land river. It differs widely from other coastal features such as a straight open shoreline or a bay, where dispersion of waste effluent can occur in at least two dimensions. For this reason, high concentrations of SSL can be found at greater distances from the source in Neroutsos Inlet than in an area such as Port Gardner Bay (Eldridge and Orlob, 1951).

That pulp mill pollution has affected the intertidal fauna in Neroutsos Inlet there is little doubt. The effects on fish are more obscure, since fish are able to survive in the deep oxygen-rich water. There are reports of fish, mainly rock cod, having been taken near the wharf at Port Alice in the vicinity of the mill sewer outfall. Divers working in waters adjacent to the mill have noted large numbers of sea-perch, rock cod, and other bottom-dwelling fish in the deep water. Occasionally there are reports of dead rockfish being found in the inlet, as during July 1955, when a number of these were collected during their last stages of life by the Fisheries atrol Vessel Pholis following a very low tide after a week of dry eather.

Small salmon runs are regularly recorded by Fisheries inspectors streams at the head of the Inlet. It is presumed that these fish equent or pass through the water layers below 5 m depth, where e oxygen supply is ample and where concentration of SSL is small. ownstream migration of salmon fingerlings is probably accom-nied by heavy mortality inasmuch as juvenile salmon tend to swim ong the surface and linger in embayments during their seaward igration. Their destruction would be unnoticed, since small salmon nd to sink when dead. It has been suggested (Wickett, personal mmunication) that pink salmon, *Oncorhynchus gorbuscha*, do not pawn in the rivers tributary to Neroutsos Inlet since juveniles of his species are small when they enter the sea and are sensitive to ollution. Since runs of pinks normally occur in other inlets of the uatsino Sound system, it is reasonable to assume that they probably annot withstand the effect of sulphite waste in Neroutsos Inlet. isheries inspectors examining Cayeghle Creek and its tributary, olonial Creek, have reported that they are favorable streams for almon spawning but are underutilized. At present, only silvers *O. kisutch*), chinook (*O. tshawytscha*) and dog (*O. keta*) salmon, which roduce much hardier downstream migrants than pinks, spawn in he streams. In the opinion of the Fisheries inspectors, Neroutsos nlet is by far the most inferior inlet of the Quatsino Sound system s a salmon producer.

It is curious that the chemical and biological properties of the ater in this Inlet were so different in 1957 from those observed in 927. It is true that in 1927 the mill was not operating at its present apacity of 220 tons per day. Furthermore, weather conditions receding the 1927 survey probably differed considerably from hose preceding the recent survey. Most of the 1957 stations were ccupied during the early morning when the water was calm and hen there was no aeration by wind mixing. However, these differences do not seem to be sufficient to explain the large differences n characteristics observed.

The change in environment due to adverse conditions created by ollution is not always a sudden sort of thing. Deterioration may be gradual process. Evidently, it is partially this type of decay which as occurred in Neroutsos Inlet. Ten years after the mill commenced peration, chemical and biological observations of the water indicated little pollutional effect from the pulp mill, and biological characteristics appeared to be normal. However, 40 years after the mill went into operation, a marked change has been noted.

Neroutsos Inlet, unlike Alberni Inlet (Tully, 1949), does not possess freshwater characteristics which would provide adequate flushing of surface waters. Because runoff from the head of the Inlet is small, there is not the large seaward flow at the surface that is present in most other inlets. Consequently, flushing of effluent must rely on the small existing stream inflows in addition to displacement by the effluent itself. There is a small net daily displacement seaward as the effluent moves back and forth with the tide. Flushing efficiency in Neroutsos Inlet is relatively small compared to that in other British Columbia inlets. With the absence of deep vertical mixing, the effluent is confined to a relatively shallow surface layer.

ACKNOWLEDGMENTS

It is a pleasure to record this contribution in honour of Professor Thomas G. Thompson, under whose guidance the author had the privilege of studying oceanography. Alaska Pine and Cellulose Limited at Port Alice provided basic information on their pulp production and supplied digestor liquor samples for standards in analysis of sea water for SSL. Their co-operation is gratefully acknowledged. Unpublished data collected in Quatsino Sound by Dr. A. H. Hutchinson and Mr. C. C. Lucas during 1927 have been used here through the courtesy of the Department of Fisheries in Vancouver, where their report was held on file.

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ON THE RELIABILITY OF FIELD MEASUREMENTS OF TEMPERATURE AND SALINITY IN THE OCEAN[1]

By

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ABSTRACT

In order to evaluate the reliability of recent field measurements of temperature and salinity we have followed the behavior of certain pairs of reversing thermometers through many reversals and have examined the distribution of closely spaced measurements of temperature and salinity at intermediate depths. The errors of measurement are comparable to those of the classical expeditions and are small with respect to sampling and other errors in the upper layers of the ocean. The effect of measurement errors on computed values of specific volume anomaly, of geopotential anomaly, and of geostrophic current speed was examined.

INTRODUCTION

Subsurface measurements of temperature and salinity are usually used by oceanographers to describe the distributions of these properties, to characterize water masses, and to derive the field of mass in the sea. From the field of mass, by means of hydrostatic computations and the geostrophic equation, it is possible to compute a measure of the field of velocity. The accuracy with which the field of velocity is known depends among other things on the accuracy of the measurements of temperature and salinity employed.

It is often assumed by oceanographers that all temperature measurements with reversing thermometers are accurate to within 0.01° and that salinity measurements have errors not greater than 0.02 $^0/_{00}$ (for example, see Sverdrup, *et al.*, 1942: 349, 54). Such estimates of error are based in part on laboratory studies of precision and accuracy, but generally they are derived from studies made in connection with the major expeditions of the late 1920s (such as METEOR, SNELLIUS and CARNEGIE).

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Now that the collection and processing of large quantities of oceanographic data have become well established routines, it is possible that different quality standards may pertain. To what extent has accuracy been sacrificed to obtain detailed coverage in space and time? To answer this we have attempted a realistic evaluation of the reliability of some recent field measurements of temperature and salinity.

TEMPERATURE

It is common practice in oceanography to measure subsurface temperature by means of protected reversing thermometers; often two such thermometers are used at a given depth. After application of an index correction and a correction for expansion of the mercury column as the thermometer warms up, the resulting corrected temperatures are averaged to obtain the accepted *in situ* temperature. Such replicate measurements have been used to estimate errors in temperature measurements, for example by Böhnecke (1932) for Meteor observations and by Hamaker (1941) for those of Snellius. The latter paper includes a summary of Böhnecke's study along with a useful general discussion of the sources and treatment of errors.

Both Böhnecke and Hamaker computed standard deviations of differences between paired thermometers on the assumption that all came from a single population. In our study it was possible to follow various pairs of thermometers through many reversals so that the data from each given pair represents a single population. With this approach it is possible to separate the variance into its random and systematic components.

The temperature measurements analysed in this paper were made for the most part with thermometers of American and German manufacture which had been calibrated at the Scripps Institution within two years of the time of use. Pairs of thermometers were chosen from the records of two long Scripps expeditions (Downwind in 1957–58 and Shellback in 1952) and of two shorter operations of the Marine Life Research program (Cruises 5704S and 5704H, both in 1957). The only criterion for choosing a pair of thermometers was that a large number of reversals be available (from 31 to 103 reversals were available for the pairs used). For each pair the difference between the corrected readings of the left and right thermometer (d_i) was calculated for the i^{th} reversal:

TABLE I. ESTIMATES OF TEMPERATURE MEASUREMENT ERRORS FROM ANALYSIS OF PAIRED THERMOMETER REVERSALS

Thermometer Pair	$\bar{d}$ (° *C*)	$s^2_{wp} \times 10^4$ (° *C*^{2})	$s^2_0 \times 10^4$ (° *C*^{2})	$s^2_s \times 10^4$ (° *C*^{2})	n
DOWNWIND					
1	0.009	2.2	1.9	0.3	35
2	0.003	1.9	1.8	0.1	44
3	0.013	2.5	1.7	0.8	43
4	0.017	3.6	2.2	1.4	41
5	0.014	2.2	1.2	0.9	42
6	0.029	4.8	0.4	4.3	43
7	0.013	2.8	1.9	0.9	43
8	0.022	2.9	0.5	2.4	54
11	0.006	0.9	0.7	0.2	80
14	0.014	1.5	0.6	0.9	79
15	0.022	3.5	1.1	2.4	31
16	0.002	0.6	0.6	0.0	54
17	0.002	0.5	0.4	0.0	75
18	0.019	2.6	0.8	1.8	59
5704 S					
36	0.005	1.4	1.3	0.1	34
35	0.005	4.7	4.6	0.1	56
13	0.001	2.8	2.9	0.0	60
17	0.008	1.9	1.6	0.3	60
47	0.021	2.6	0.5	2.1	53
5704 H					
3	0.003	2.4	2.4	0.0	68
19	0.015	2.0	0.9	1.1	61
4	0.005	3.3	3.2	0.1	59
12	0.007	0.8	0.5	0.3	67
7	0.018	3.1	1.4	1.6	69
SHELLBACK					
29	0.008	3.0	2.7	0.3	93
35	0.008	3.0	2.7	0.3	92
96	0.014	1.9	0.9	0.9	103
94	0.012	1.5	0.9	0.7	102
79	0.023	4.8	2.1	2.8	103
101	0.017	1.9	0.4	1.5	101
26	0.009	2.5	2.2	0.4	56
89	0.008	0.7	0.5	0.3	99
Over-all Average	0.012	2.4	1.5	0.9	—

$\bar{d}$ is mean difference, s^2_{wp} the estimate of within-pair variance, s^2_0 the estimate of variance of random error, s^2_s the estimate of variance of systematic error, and n the number of reversals used.

$$d_i = (t_L - t_R)_i.$$

verages of differences ($\bar{d}$) for n reversals of the various pairs are sted in Table I.

If there were no systematic difference between the thermometers f a pair, then the average of differences would be zero. However, most cases (85 $^0/_0$) the mean difference is significantly different om zero at the 5 $^0/_0$ level of significance, the grand mean difference ing 0.012° with a range from 0.001 to 0.030°. The source of this tematic difference between thermometers presumably lies in their ibration or in a shift in zero point. On the average this relative stematic error will underestimate the true systematic error (since he true temperature is unknown). The data suggest that differences etween paired thermometers are commonly as great as 0.01° and hat the average systematic error of a single thermometer is at east 0.005°.

The variance of the two corrected readings from a pair of thernometers averaged over a large number of reversals provides a ood estimate of the within-pair variance, σ_{wp}^2, through use of the quation[2]

$$s_{wp}^2 = \frac{\sum_{1}^{n} d_i^2}{2n}.$$

This variance is equal to the sum of a systematic component, σ_s^2, and of a random component, σ_0^2. The relative contributions of hese two components can be determined since the random compoent can be estimated[3]. The readings of the two thermometers of pair are independent, and the variance of the difference in corected readings, d_i, is

$$\sigma_{d_i}^2 = \sigma_L^2 + \sigma_R^2.$$

Then the average random component of variance of a given thermometer is

$$\sigma_0^2 = \sigma_{d_i}^2/2;$$

$\sigma_{d_i}^2$ can be estimated by

$$s_{d_i}^2 = \sum_{i=1}^{n} \frac{(d_i - \bar{d})^2}{n-1}.$$

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[2] The equation for the weighted average of a set of variances, each of which is alculated from two observations.

[3] The systematic component can also be estimated directly, since $s_s^2 = \bar{d}^2/2$.

Total within-pair variance and variances of the random and systematic components are listed for 32 pairs of thermometers (Table I). In terms of standard deviation, the over-all estimates of total, random and systematic errors of single thermometer readings average 0.016°, 0.012° and 0.010° respectively.

Errors in reversing thermometer temperature measurements may also be estimated by using data from special hydrographic casts with closely spaced Nansen bottles. Such casts have frequently been made to intermediate depths in order to check the pressure calibrations of unprotected thermometers. In certain cases the slope of the temperature-depth curve is sufficiently constant that a regression line may be fitted to the data. Residuals from this line may then be interpreted as the sum of random and systematic errors on the assumption that in the particular situation the relation is truly linear. Strictly speaking, this assumption is never completely valid, and this method presumably overestimates the error (since the residuals contain a component due to the nonlinear trend). In the statistical model, errors in relative depth are considered small in relation to the temperature errors.

Of the large number of special casts taken during the last ten years at the Scripps Institution of Oceanography, only a few were found to be suitably linear for analysis. On these casts, thermometer separation ranged from 2 to 25 m; in the summary of results (Table II) the casts with 25 m spacing are listed separately from those with separations of 2 to 10 m since there appeared to be a significant difference between the two groups[4]. The square root of the weighted average of estimates for closely spaced thermometers is 0.020° (with a range of 0.012° to 0.030°) whereas that for casts with 25 m spacing is 0.027°. The former value is considered a more valid estimate since, in the case of the widely spaced thermometers, the casts cover such a vertical distance that the assumption of linearity is less justifiable.

In summary these studies lead to the following conclusions. The standard deviation of random error of a single thermometer is 0.012°. This random error is superposed on a systematic error, the standard deviation of which is 0.010°. The upper limit of combined errors of a single thermometer is estimated by a standard deviation

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[4] Note that each thermometer reading has been considered independent, although there were usually two thermometers at each depth.

ABLE II. Estimates of Temperature Measurement Errors from Analysis of Closely Spaced Observations

Cruise	*Depth Range* (*m*)	*Spacing* (*m*)	s_{zT} (° *C*)	*n*
5404 F	502–520	2	0.013	19
H-36	893–933	5	0.014	11
C-35	884–910	3	0.019	16
B-33 (a)	921–945	2	0.014	22
B-33 (b)	956–976	2	0.016	23
B-35	943–963	2	0.018	19
Y-32	1240–1264	3	0.014	17
B-20	921–945	2	0.027	18
B-19	953–1008	5	0.013	16
C-19 (a)	985–1035	5	0.020	18
C-19 (b)	989–1039	5	0.018	18
5404 F	503–521	2	0.012	19
Q-4	479–528	5	0.021	18
5807 S	405–478	10	0.029	15
5807 B	425–521	9	0.018	22
5807 O	424–573	10	0.030	31
C-21 (a)	815–935	25	0.017	12
C-21 (b)	765–951	25	0.027	18
H-25	785–981	25	0.022	17
C-25	781–1001	25	0.029	16
B-25	780–1003	25	0.019	18
C-27	818–995	25	0.014	13
C-24 (a)	655–879	25	0.038	18
C-24 (b)	668–887	25	0.031	19
H-24	640–852	25	0.023	14
H-24	758–1004	25	0.019	21
H-23	670–998	25	0.032	23
H-23	779–926	25	0.019	14
B-23	752–975	25	0.023	18
C-23 (a)	646–981	25	0.028	28
C-23 (b)	693–1011	25	0.035	28
C-22	762–1004	25	0.026	21
C-22	676–898	25	0.027	19
B-22	703–1022	25	0.021	26

s_{zT} is standard error of regression, and n the number of observations used.

f 0.020° (from the analysis of closely spaced thermometers) and he lower limit by 0.016° (from the analysis of within-pair variance).

These estimates of error in temperature measurements are comparable to those made by other authors. In Hamaker's (1941) summary of METEOR and SNELLIUS observations, standard errors of a single observation range from 0.008 to 0.012° depending on the type of thermometer used (compared to our value of 0.016°). The estimated standard deviation of systematic error for SNELLIUS observations is 0.007° (compared to our value of 0.010°). From table I of Thomsen's (1937) discussion of DANA observations, we have computed the standard deviation of combined errors to be 0.015° (compared to our value of 0.016°). Sverdrup's (1944) discussion of CARNEGIE data does not contain estimates in a form comparable with ours, except that his grand mean difference between paired thermometers seems to be essentially the same as ours (about 0.012°).

All of the above estimates refer to errors of a single thermometer reading. When a temperature measurement is obtained by averaging the corrected readings of two thermometers, the standard deviation is reduced by the factor $1/\sqrt{2}$. Our results show that the 95 $^0/_0$ confidence limits of random errors for a two-thermometer average are ±0.017°.

SALINITY

Duplicate chlorinity titrations conventionally run on sea water samples are not sufficiently independent to be used in an analysis of errors. Laboratory tests of precision, where a skilled operator carries out carefully replicated analyses, will presumably lead to a smaller estimate of error than is valid for more heterogeneous field data. It is possible to obtain some idea of the magnitude of errors in such data if we refer to the same special hydrographic casts with closely spaced Nansen bottles used above in the analysis of temperature errors; however, compared to the temperature data there were fewer casts with reliable salinity values, and, since only one salinity resulting from a duplicate titration is assigned to each sampling depth, only half as many observations were available from each cast. As before, casts were selected on which salinity appeared to change with depth in linear fashion, and residuals from the regression line were computed. The results are summarized in Table III.

The estimates of standard deviation for the various casts range from 0.005 to 0.032 $^0/_{00}$, and the square root of the weighted average of the estimated variances is 0.018 $^0/_{00}$. On the assumption that deviations are normally distributed, the 95 $^0/_0$ probability limits are stimated by ± 0.036 $^0/_{00}$. This error estimate is considered an upper imit, since the deviations presumably include a component due to he nonlinearity of the salinity-depth relationship.

There are few estimates of error in the literature with which our esults can be compared. Based on statistical analysis of results obtained by skilled operators in a shore based laboratory, Strickland (1958) has reported 95 $^0/_0$ confidence limits as ± 0.017 $^0/_{00}$, implying a standard deviation of 0.0085 $^0/_{00}$. Hardon's (1941) summary of Snellius and Meteor observations has assumed that duplicate analyses of single samples are completely independent; thus his estimates, expressed as standard deviation in salinity units, namely 0.008 $^0/_{00}$ for Snellius and 0.021 $^0/_{00}$ for Meteor, are presumably low.

ABLE III. Estimates of Salinity Measurements Errors from Analysis of Closely Spaced Observations

Cruise	*Depth Range* (*m*)	*Spacing* (*m*)	s_{zS} ($^0/_{00}$)	*n*
5810 H	529–679	10	0.012	17
5811 P	483–612	10	0.022	14
5807 O	415–573	10	0.005	16
5807 S	405–551	8	0.029	17
5810 P	449–597	10	0.017	16
5807 B	469–538	9	0.014	9
B-20	921–985	5	0.021	15
B-33 (a)	956–976	2	0.032	15
B-33 (b)	921–945	2	0.030	10
H-36	888–933	5	0.016	11
C-35	881–910	3	0.014	15
C-19	955–1035	5	0.017	15
H-35	946–973	3	0.010	15
B-35	943–963	2	0.023	11
5810 S	342–568	10	0.017	23

s_{zS} is standard error of regression, and n the number of observations used.

An estimate more analagous to ours comes from comparison of shipboard analyses of 18 Snellius samples with later replicate analyses by T. G. Thompson using the Volhard method (Hardon, 1941). Since the Volhard method is known to be more accurate than the usual Mohr titration, it is not unreasonable to assume that

Thompson's values represent the true salinity; in salinity units, his results were on the average 0.009 ‰ low, with a standard deviation of 0.023 ‰.

SAMPLING AND OTHER ERRORS

The estimates of error discussed above refer only to measurements at given depths in the sea. The depths themselves, which are derived from measurements with reversing thermometers, may be in error. Hamaker (1941) has estimated a standard error of depth determination of 4 m at all depths. A more recent study, by Whitney (1957), suggests that below 1000 m an accuracy of about 0.5 % can be expected; at lesser depths the percentage error may be greater.

It is possible to use our estimate of error in temperature measurement to calculate the associated error in thermometric depth determination. Thermometric depth, D, is computed from the equation

$$D = \frac{10\Delta t}{Q\varrho_m},$$

where Δt is the difference between temperature indicated by the unprotected thermometer and the true *in situ* temperature, Q is the pressure coefficient of the unprotected thermometer in °C/kg/cm², and ϱ_m is the mean density of the water column above the level of reversal in gm/cm³. The variance of D equals

$$\sigma_D^2 = \left(\frac{10\Delta t}{Q\varrho_m}\right)^2 (v_Q^2 + v_{\Delta t}^2),$$

where v_Q^2 and $v_{\Delta t}^2$ represent the relative variances of Q and Δt respectively.

If Q is known exactly, it can be shown that random errors in thermometric depth resulting from errors in temperature measurement alone (using two protected thermometers and one unprotected thermometer at a depth) is ± 4 m (two standard deviations) regardless of depth. If, as Whitney (1957) suggests, the pressure factor, Q, is accurate within ± 0.0001 °C/kg/cm² (we assume that this is one standard deviation), random errors in depth determination increase slightly with depth, being about ± 7 m at 3000 m. If Q is a function of temperature or pressure rather than of a constant, the use of a constant value will introduce a systematic error.

In the upper 100 m or so, where vertical gradients are greatest, determination of depth may be somewhat more accurate, since it is based on wire angle and wire length rather than on unprotected thermometer measurements. In the thermocline, where the vertical temperature gradient may be as great as 0.5 °/m, a one meter depth error causes a 0.5° temperature error; the same depth error in a strong halocline (2 $^0/_{00}$ in 50 m) causes a salinity error of 0.04 $^0/_{00}$. At a depth of several thousand meters, where the vertical temperature gradient is about 0.002 °/m, a 5 m depth error leads to a temperature error of only 0.01°; at such depths salinity gradients are so small that depth errors have a negligible effect on salinity measurement.

Interpolation errors are introduced whenever values are assigned to depths other than those of measurement. These errors are difficult to estimate, because they depend not only on the relation between the vertical spacing of observations and the shape of the depth distribution or characteristic curve of the property in question but also on the interpolation method employed. Such methods range from objective linear, logarithmic or parabolic interpolations to subjective analyses of characteristic curves based on data from neighboring stations. Without knowing the true vertical distribution of a property, *i. e.*, the function which interpolation is being used to approximate, it is hard to evaluate errors thus introduced. It is unlikely, however, that the interpolation errors are smaller than those of the original measurements.

The interpolation error can be considered a sampling error in space. Sampling "errors" in time occur when a measurement is assumed to represent conditions over a period of time longer than that required for the measurement. The magnitude of error depends both on the time interval assumed and on the rate of change of the property in question. Such errors must vary considerably from place to place; an estimate of their magnitude can be obtained from time series data such as those from anchor stations.

Seiwell (1939), in an analysis of an eight-day anchor station in the western Sargasso Sea, found that the rate of change of temperature at various standard depths was greatest at those depths where the maximum vertical temperature gradient occurred. In the summer thermocline (at 100 m) an average daily range of 0.9° was observed; in the lower part of the permanent thermocline (at 1000 m) the average daily range was 1.2°. Hamaker (1941), in an examination of data from four anchor stations in the East Indian Archipelago, has reported standard deviations "due to internal waves" of 1.15° at 100 m (in the thermocline), decreasing to 0.12° at 800 m; similar calculations by Hamaker, using data from nine METEOR anchor stations, showed a standard deviation of 1.2° at 25 m, decreasing to 0.01° at 1200 m.

We have examined data from two eight-day anchor stations (70.90 and 70.130) which were taken in October 1950 in the region of the California Current. Reid (1956), in a study of these data, found no sign of any periodic phenomena with periods up to 27 hours, although on an anchor station farther inshore he found evidence of internal waves of semidiurnal period. (The presence of prominent periodicities makes statistical treatment difficult because measurements taken at constant time intervals cannot then be considered independent. Of course, even the absence of obvious periodicity does not guarantee that the data are not autocorrelated).

At both stations, oscillations with apparent periods longer than 27 hours were often present in the upper few hundred meters. These long oscillations can be considered trends; the "random" deviation from the trend, as estimated by the variate-difference method (Kendall, 1948: 387), is an indication of error introduced by assuming that a given measurement represents some period up to a day. Deviations from an eight-day mean, on the other hand, are indicative of error introduced by assuming that a given measurement represents a period of up to a week. At or below the depth where these two deviations are the same, no trend is apparent.

Standard deviations of temperature and salinity at selected depths at these two stations, with and without trend, are summarized in Table IV. Note that measurement, interpolation and depth errors are included in these deviations and that below 300 m the estimates are less reliable than those above 300 m, since only a fourth as many observations were available. Near the surface, where the largest vertical gradients occur, large changes (1–2° in temperature, 0.1 $^0/_{00}$ in salinity) take place. At greater depths the daily and weekly deviations are much smaller, although they can be greater than those of measurement alone even at 500 and 1000 m. These results are not substantially different from those of Hamaker's analysis in the East Indian Archipelago mentioned earlier. In regions with small vertical gradients or less pronounced vertical oscillations one would expect small changes with time.

DYNAMIC CALCULATIONS

For a general description of distributions of temperature, salinity r density, the various errors discussed above are of little significance. nly at great depths is it likely that measurement errors will be itical for descriptive purposes. However, when temperature and linity distributions are used for computing density parameters nd horizontal pressure gradients, then measurement, sampling, and her errors can be important. The effect of sampling errors due to rtical oscillations, discussed by Seiwell (1939), Reid (1956) and hers, will not be treated further here.

We have examined the effect of measurement and depth errors on e calculation of geopotential anomaly and geostrophic current peeds. Geopotential anomaly, ΔD, is determined from an approximation of the integral

$$\Delta D = \int_0^p \delta\, dp \doteq \sum_i (\bar{\delta} \Delta p)_i,$$

ABLE IV. Examples of Time Sampling Errors from Analysis of two Eight-Day Anchor Stations

Depth (*m*)	s_{T° *w/trend*	s_{T° *w/o trend*	$s_{S^\circ/_{oo}}$ *w/trend*	$s_{S^\circ/_{oo}}$ *w/o trend*
Station 70.130				
30	0.13	0.08	0.08	0.06
50	1.17	1.12	0.12	0.10
75	0.67	0.57	0.10	0.08
150	0.34	0.21	0.09	0.08
300	0.13	0.11	0.03	—
500	0.16	—	0.05	—
1000	0.04	—	0.09	—
Station 70.90				
30	2.18	1.61	0.07	0.04
50	0.79	0.57	0.14	0.09
75	0.23	0.16	0.14	0.09
150	0.07	—	0.04	—
300	0.05	—	0.02	—
500	0.11	—	0.02	—
1000	0.05	—	0.02	—

s is estimate of standard deviation from eight-day mean (*w/trend*) or with trend emoved (*w/o trend*). Down to 300 m, 60–64 observations were available for each tation; below 300 m, 14–16 observations were used.

and the variance of geopotential anomaly is

$$\sigma^2_{\Delta D} = \sum_i (\Delta p_i)^2 \sigma^2_{\delta_i}.$$

The variance of specific volume anomaly at a given depth, $\sigma^2_{\delta_i}$, consists of two principal terms

$$\sigma^2_{\delta_i} \doteq \sigma^2_e + \sigma^2_z \left(\frac{\partial \delta}{\partial z}\right)^2,$$

where σ^2_e is the variance of measurement errors and $\sigma^2_z\ (\partial \delta / \partial z)^2$ the variance of depth errors. As an approximation, the terms are additive, since the first is primarily salinity dependent, the second primarily temperature dependent.

From our analysis of temperature and salinity measurement errors, the value of the first term can be computed, since the standard deviation of specific volume anomaly due to such errors (assumed here to be 0.01° in temperature and 0.015 $^0/_{00}$ in salinity) is approximately 1.5 cl/T (centiliters per metric ton, or 10^{-5} cm^3/g)[5]. This is dominated by salinity measurement errors, the effect of temperature measurement errors being an order of magnitude smaller. Below the surface layer the second term is much smaller than the first; even with an extremely large vertical gradient at depth (for example, 0.24 cl/T/m at 700–800 m for ATLANTIS St. 5203), it is an order of magnitude smaller. Near the surface, although $\partial \delta / \partial z$ may be large, the layer for which this is true is relatively thin (*i.e.*, Δp is small) and the depth error is small, so that $\sigma^2_{\Delta D}$ can be approximated by

$$\sigma^2_{\Delta D} \doteq \tfrac{1}{2} \sigma^2_e \sum_i (\Delta p_i)^2.$$

Since measurement errors do not vary significantly with depth, the variance of geopotential anomaly is quite sensitive to the number of pressure intervals used in the integration. For example, between the surface and 1000 *db*, $\sum (\Delta p_i)^2$ for one layer 1000 m thick is 10^3 times greater than that for a thousand layers 1 m thick. If one uses the so-called "standard" depth intervals (Sverdrup, *et al.*, 1942: 357), the standard error in geopotential anomaly (0 over 1000 *db*) is 0.004 dyn m. The standard error of the difference in geopotential anomaly (0 over 1000 db) between two stations is 0.0056 dyn m.

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[5] This computation assumes the validity of the temperature-chlorinity-density relationship used in oceanographic tables (LaFond, 1951).

Thus one can say that the measurement error of this difference is 0.011 dyn m (two standard deviations); for a pair of stations at 30° of latitude separated by 100 km, the resulting error in geostrophic current speed is ± 1.5 cm/sec.

SUMMARY

By observing various pairs of thermometers through many reversals and by examining the scatter of data on temperature-depth curves where observation points were closely spaced, we have obtained estimates of the measurement errors in temperature data obtained in the field. These estimates, expressed as standard deviations for averages of two thermometer readings, are as follows:

total error	0.014°	upper limit, from temperature-depth curves
	0.011°	from paired thermometer analysis
random error	0.009°	
systematic error	0.007°	

An upper limit of measurement error in salinity data from the field, obtained from an analysis of salinity-depth curves, is 0.018 $^{0}/_{00}$ standard deviation). Both temperature and salinity measurement errors as thus estimated are not significantly different from comparable estimates by previous investigators.

In the upper layers of the ocean other errors may be significantly greater than those of measurement. This is particularly true in the upper few hundred meters where vertical gradients of temperature and salinity are usually large. Here sampling errors due to vertical oscillations and errors resulting from uncertainty in depth determination may be as large as 1 to 2° and 0.1 $^{0}/_{00}$. At greater depths, where vertical gradients are small, such errors are comparable to measurement errors.

The effect of salinity measurement errors on the determination of specific volume anomaly is much greater than that of temperature errors and amounts to a standard deviation of about 1.5 cl/T. The resulting standard deviation of geopotential anomaly (0 over 1000 db) for a station on which standard depth intervals are used is 0.004 dyn m. The measurement error of the difference between two such stations is ± 0.011 dyn m (two standard deviations), and at 30° latitude and 100 km separation, the corresponding error in geostrophic current speed is ± 1.5 cm/sec.

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DIURNAL STUDY OF PHYTOPLANKTON PIGMENTS

AN *IN SITU* STUDY IN EAST SOUND, WASHINGTON[1]

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ABSTRACT

The effect of light intensity on the quantities of chlorophyll and carotenoid pigments in a natural marine diatom community has been observed. Marked daily fluctuations in the quantities of these pigments, which showed highest concentrations around mid-day and at night, resulted from changes in quantities within the cells. Rates of synthesis and decomposition throughout the day have been computed. Highest cellular concentrations of chlorophyll and carotenoid pigments corresponded to optimal light intensities for photosynthesis. The differential effect of light on chlorophyll *a* and on carotenoid pigments, where chlorophyll changes are more extreme, caused the ratios of these pigments to change during the day. The significance of this change is discussed.

INTRODUCTION

Plant pigment destruction and photosynthetic inhibition by strong light may be observed most easily in land plants and algae which are adapted to living at low light intensities. The typical "shade" characteristics of planktonic algae suggest that, in the surface of lakes and oceans, high and low daily light intensities cause marked fluctuations in the pigment content of planktonic populations. In a recent paper, Yentsch and Ryther (1957) observed a diurnal fluctuation in the chlorophyll content of a natural population of phytoplankton enclosed in a floating carboy; highest chlorophyll *a* concentrations were observed during morning and afternoon and lowest concentrations around mid-day and early evening. Although other workers have described diurnal variations in chlorophyll concen-

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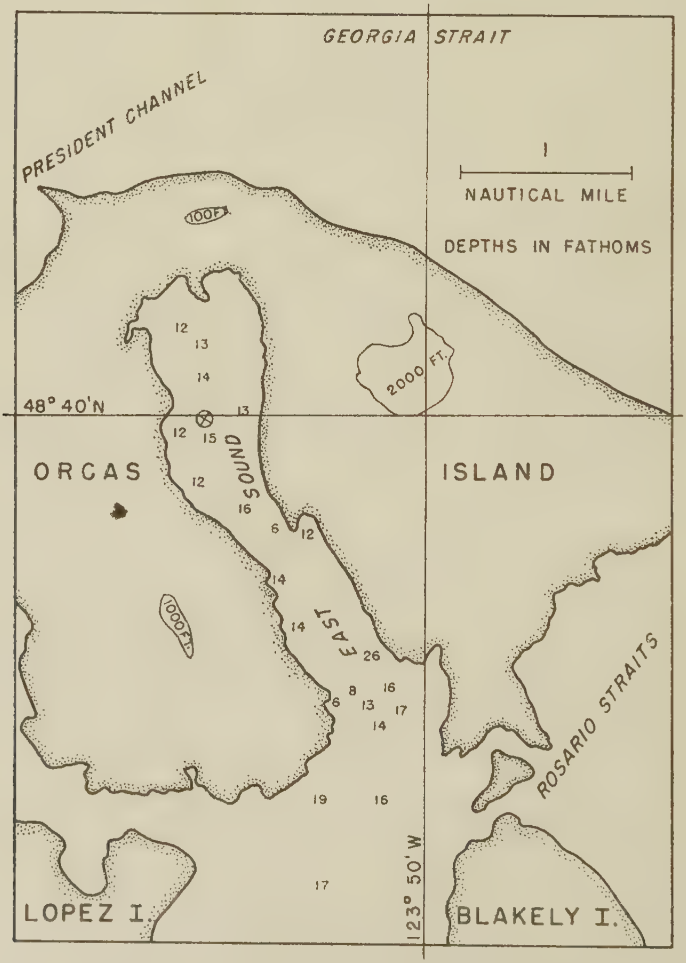
Approximately thirty years ago Dr. T. G. Thompson, working with Gran (Gran and Thompson, 1930), recognized the high phytoplankton productivity of East Sound. Since then, whenever possible, he has encouraged students interested in phytoplankton problems to work in the area.


GEORGIA STRAIT
PRESIDENT CHANNEL
1
NAUTICAL MILE
DEPTHS IN FATHOMS
100FT
2000 FT.
12
13
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48° 40'N
13
12
15
SOUND
ORCAS
ISLAND
12
16
6
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14
26
8
16
6
13
17
14
ROSARIO STRAITS
19
16
17
123° 50' W
LOPEZ I.
BLAKELY I.

Figure 1. Map of East Sound; circled cross indicates station location.

ations (see Rabinowitch, 1945: chapt. 15), little information is ailable concerning the rate of pigment synthesis and decomposition der natural conditions of illumination. Where laboratory studies ve been made, few have approached intensities comparable to d-day values. Virgin (1955) observed optimal chlorophyll *a* synesis in barley leaves at 500 foot-candles, while Halldal (1958) obrved highest concentrations of chlorophyll and carotenoid pigents in blue-green algae at 200–400 and at 400–800 foot-candles, spectively.

During the summer of 1954, while in residence at the University Washington's Friday Harbor Marine Laboratory, we conducted diurnal study of phytoplankton pigments throughout a water lumn in East Sound, Orcas Island (Fig. 1). The purpose of this udy was to observe the relationship of light intensity to chloroyll and carotenoid pigment concentrations in a natural crop of ytoplankton.

The writers are indebted to Dr. R. H. Fleming who made arrangeents for use of the R. V. BROWN BEAR, to Captain Princehouse d crew for their cooperation, and to Carey McAllister, Francis arris, Ruth Palmer, Alan Duxbury, and Tamio Yamagiwa who ded in shipboard operations and analyses. This work was partially pported by the U.S. Office of Naval Research (Contract N8ONR–20/III Project NR083012) and by the National Research Council Canada.

METHODS AND PROCEDURES

Water samples for phytoplankton pigments were taken with the ansen-Knudsen three-liter closing bottle. After each sample had een divided into approximate halves, each half was filtered on ipboard through a millipore type AA filter following the procedure tlined by Creitz and Richards (1955). At the shore laboratory the ncentrate from half of each sample was scraped from the filter d allowed to settle in a measured volume of 4 $^0/_0$ formalin. Cellunting was done in a modified Sedgwick-Rafter counting chamber known volume under 100 and 400 × magnification. Pigment traction and determination were also done at the shore laboratory, llowing the method outlined by Richards with Thompson (1952). hlorophyll *a* values are expressed in milligrams, while chlorophyll *c* d carotenoid pigments are given in specific plant pigment units;

one specific pigment unit of plant carotenoid pigment is closely equivalent to one milligram.

Temperature and salinity were measured with Nansen bottles fitted with reversing thermometers. Chlorinity was determined by the Mohr method as modified by Thompson (1928). Densities were calculated from the hydrographic tables of Knudsen (1901). Light intensities in the water column were measured with a standard Clarke submarine photometer which was fitted with a green filter and which had previously been calibrated against a Weston foot-candle meter. Intensities for given depths were corrected by means of the foot-candle extinction coefficients for green light given by Utterback and Wilson (1940).

Because of the prevailing clear weather and a small range in tide in mid-July 1954, it was decided to occupy a station in East Sound on July 13. At approximately 0900 the r. v. Brown Bear dropped anchor at the head of the Sound in 27 m of water (Fig. 1). Sampling periods were 1015, 1615, 2100, and 2400 on July 13, and 0520 and 0845 on July 14. During each sampling period a six-bottle cast for phytoplankton collections was made at depths of 0, 3, 5, 10, 15, and 25 m. A second six-bottle cast at the same depths followed, using Nansen bottles. While the thermometers were coming to temperature, a bathythermograph and the light meter were lowered.

Water Mass Conditions, July 13–14. Stratification in the water column persisted day and night. Surface temperatures varied from 11.67 to 12.78° C, following a trend indicative of diurnal heating and cooling. The maximum thermal gradient was between 3 and 5 m, below which the temperature was constant at 10.0° C. During daylight hours of July 13 the surface waters were practically flat calm; between 1000 and midnight a 10 knot breeze ruffled the surface, but no detectable deepening of the mixed layer was evident. Salinities throughout the water column showed almost no variation throughout the day, the salinities at the surface being 28.91 $^0/_{00}$; those at the bottom 29.81. The average difference between σ_t at the surface and at 25 m was 1.81.

Poor flushing in East Sound can be expected because of relatively little freshwater inflow, the general morphology of the basin, and a small sill which partially obstructs the entrance and thus restricts circulation.

Measurements of oxygen and inorganic phosphate in the surface vater during the study revealed a marked inverse correlation beween these properties. Supersaturated oxygen values were conistently observed during the day, and the ratio between the pparent oxygen utilization and phosphate were comparable to ratios ssociated with oxidation or reduction of organic material (Redield 1934, 1942; Fleming 1940).

These observations, of a widely varying nature, lead us to conlude that advective influences were minimal during this study. The iscussion which follows assumes that advection and eddy diffusion re of negligible magnitude and that the same populations were mpled repeatedly.

Phytoplankton Community, July 13–14. The phytoplankton popuation in East Sound comprised almost exclusively diatoms belongng to the genera, *Chaetoceros*, *Skeletonema*, *Nitzschia*, *Asterionella*, *halassiosira*, *Thalassionema*, *Biddulphia*, and *Navicula*. Of these he most abundant species were, *Skeletonema costatum*, *Chaetoceros ebilis*, *C. decipiens*, *Nitzschia closterium*, *N. delicatissma*, *Thalassioira nordenskioldii*, and *Asterionella japonica*. Diatom counts alone or surface waters exceeded 3×10^6 cells per liter. Dinoflagellates elonging to the genera *Peridinium*, *Dinophysis*, and *Ceratium* did not exceed 2×10^4 cells per liter.

ABLE I. CELL NUMBERS $\times 10^6$ IN ONE LITER, EAST SOUND, JULY 13–14, 1956

Depth (m)	*Sampling Periods*						
	July 13					*July 14*	
	1015	1230	1615	2100	2400	0520	0845
0	3.0	8.0	18.5	31.0	24.0	25.0	31.0
3	9.0	7.5	25.0	31.0	41.0	31.2	36.0
5	18.0	22.1	22.0	18.5	15.5	28.0	28.0
10	13.0	23.3	26.0	9.0	13.0	10.5	10.7
15	5.0	14.5	11.0	5.3	7.0	11.5	8.3
25	9.0	7.0	7.5	6.5	5.7	6.4	4.3

The cell counts (Table 1) showed that there was an active flowerng in the upper 3 m, with cell numbers at the surface increasing 30-fold during the July 13–14 period. During hours of most intense llumination, cell numbers increased at all depths except at 25 m. Maximum numbers occurred between 5 and 10 m during the brightst portion of the day, whereas during darkness the largest numbers ccurred between the surface and 3 m.

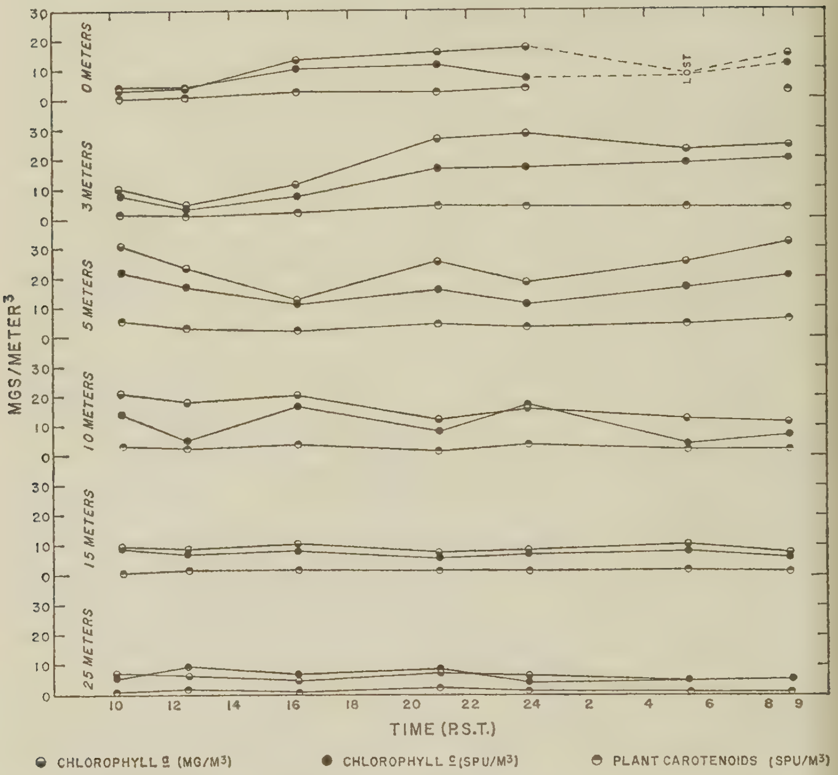

Figure 2. Concentrations of chlorophyll *a* and *c* and carotenoid pigments in East Sound, July 13 and 14.

Diurnal Variations in Phytoplankton Pigments. Fig. 2 illustrates pigment measurements at each depth plotted as a function of time. Largest concentrations of all plant pigments were found between 3 and 10 m in the region of the thermocline while lowest concentrations were observed at the surface and at 15 and 25 m. Highest concentrations of pigments were observed at 5 m during the morning (0845, 1015) and at 10 m in the afternoon (at 1600). At 2400 and 0520 the depth of greatest pigment concentration was at 3 m. Pigment values at the 15 and 25 m level remained more nearly constant throughout the day. Chlorophylls at 0, 3, 5, and 10 m underwent marked fluctuations from day to night. For example, chlorophyll *a* values at 0 and 3 m were five times higher at midnight than at mid-day. Although all pigments at the 5 m level showed a steady decline from 1015 to 1615, the decrease there was not as great as that observed at the 0 and 3 m levels. Chlorophyll *a* values at 10 m showed only slight variations while chlorophyll *c* values at this depth fluctuated considerably. Both chlorophylls were relatively constant at the 15 and 25 m levels.

The extreme changes in chlorophyll content in surface waters throughout the day were not accompanied by similar extreme changes in carotenoid pigments. Thus the pigment ratios were greatly altered throughout the day. This is best illustrated by comparing proportions of chlorophyll *a* to carotenoid pigments (Table II). The Chl *a*:Carot ratio ranged from 7.0 to 3.1. In general it tended to be higher in the early morning and at night in surface waters, but at depths greater than 3 m it was higher during mid-day.

TABLE II. Observed Chl^{a}: Carot Ratios in East Sound

Depth (m)	*Depth Aver.*	*Sampling Times*						
		0520	0845	1015	1230	1615	2100	2400
0	5.34	—	4.75	6.37	5.13	4.72	6.63	4.45
3	5.81	5.75	6.99	5.34	5.10	5.70	5.90	5.91
5	5.55	5.28	5.09	6.03	6.96	4.64	5.62	5.26
10	5.36	4.62	4.59	6.12	6.61	5.21	6.40	3.98
15	5.71	5.07	7.05	6.44	5.95	5.19	5.41	4.89
25	4.48	4.47	3.77	5.79	3.50	5.25	3.18	5.40
Daily Averages		5.03	5.43	6.51	5.54	5.11	5.52	4.98

Changes in the Pigment Concentration of Cells. At times, changes in the concentration of pigment could be associated with comparable fluctuations in cell numbers (Table I); however, at other times, pigment fluctuations were too great to be accounted for by an increase or decrease in the number of cells, hence these must have resulted from changes in cellular contents. The diurnal trend of cellular content was observed at all levels except at 25 m (Fig. 3), and it was found that the amounts of chlorophyll *a* per cell were low at 0, 3, 5, 10, and 15 m during mid-day but were high at these same depths at 0845, at 1015, at 2100, and again at 2400. During daylight hours, above 3 m, chlorophyll *a* diminished 2- to 3-fold, whereas below 3 m only small decreases occurred after 2100. The

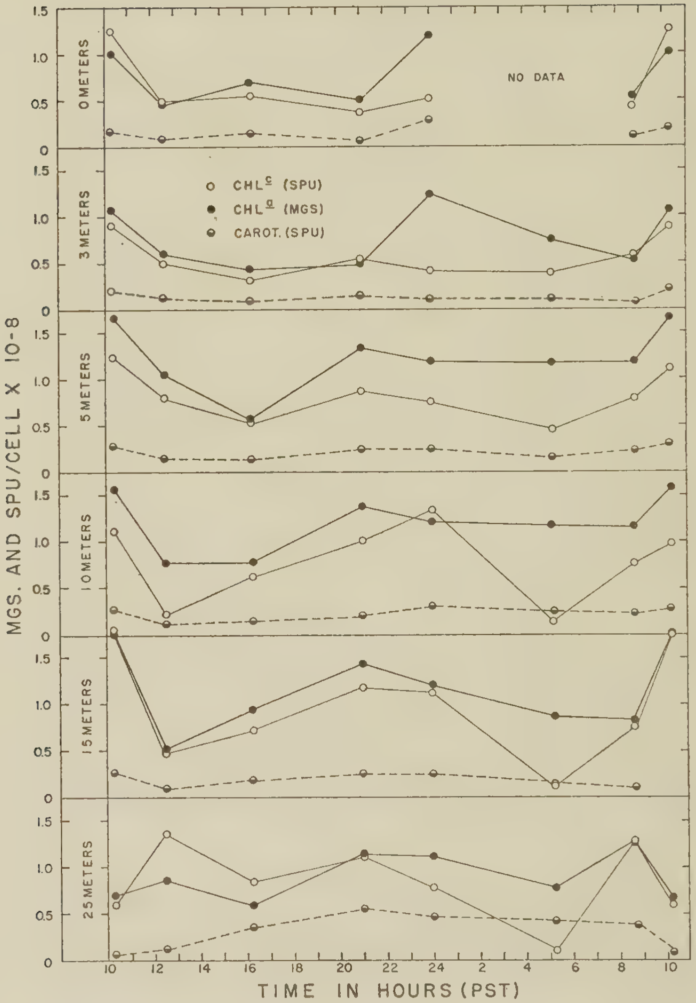

Figure 3. Chlorophyll and carotenoid pigment concentrations per cell in East Sound, July 13 and 14.

large decreases in chlorophyll *a* per 10^8 cells at the surface and at 3 m during darkness was probably due to the consummation of cell divisions started in light. The general trend of chlorophyll *c* followed chlorophyll *a*; however, deviations did occur which indicate that these two chlorophylls were not in phase (Table III). The ratios

TABLE III. RATIO OF Chl^a: Chl^c IN EAST SOUND

Depth (m)	*Depth Aver.*	*Sampling Times*						
		0520	0845	1015	1320	1615	2100	2400
0	1.31	—	1.26	0.86	0.94	1.26	1.34	2.40
3	1.46	1.90	1.19	1.24	1.18	1.36	1.54	1.62
5	1.42	1.60	1.49	1.38	1.31	1.05	1.54	1.60
10	3.28	13.10	1.46	1.44	3.43	1.22	1.38	0.91
15	2.12	8.02	1.10	0.97	1.14	1.32	1.23	1.09
25	1.42	3.73	0.99	1.13	0.64	0.63	1.02	1.41
Daily Averages		5.65	1.25	1.17	1.43	1.14	1.34	1.51

of Chl a:Chl c range from a high of 13.10 to a low of 0.86. Although no consistent trend in the ratio of these chlorophylls is indicated, the trends differed most during hours of darkness and early morning. Compared to the magnitude of the chlorophyll changes throughout the day, the carotenoid pigment per cell at that time was almost constant. Differences between the rates of change of chlorophyll and carotenoid pigments is further shown when the rates of synthesis and decomposition are computed for each pigment.

Comparison of the rate of change in cellular chlorophyll a and c and carotenoid pigments is shown in Fig. 4. These rates have been computed for sampling intervals, using concentrations at the beginning and end of each interval. The rates are expressed at each depth in milligrams or in specific plant pigment units per cell per hour. At depths other than 25 m, the highest rate of pigment increase occurred during the morning between 0845 and 1015, the maximum rate of synthesis during this period being observed at 15 m. Between 1015 and 1230, chlorophyll a and carotenoid decreased at all depths except at 25 m, with the maximum again occurring at 15 m. Between 1230 and 1615, little synthesis or decomposition was observed, and, excepting surface observations, small rates of synthesis were observed between 1615 and 2100. Thereafter, during darkness, only small rates of synthesis, if any, were observed although marked rates of decomposition were apparent at times. The active processes of chlorophyll synthesis and decomposition are strikingly apparent. Chlorophyll a rates of synthesis and decomposition are approximately five times greater than the carotenoid rates.

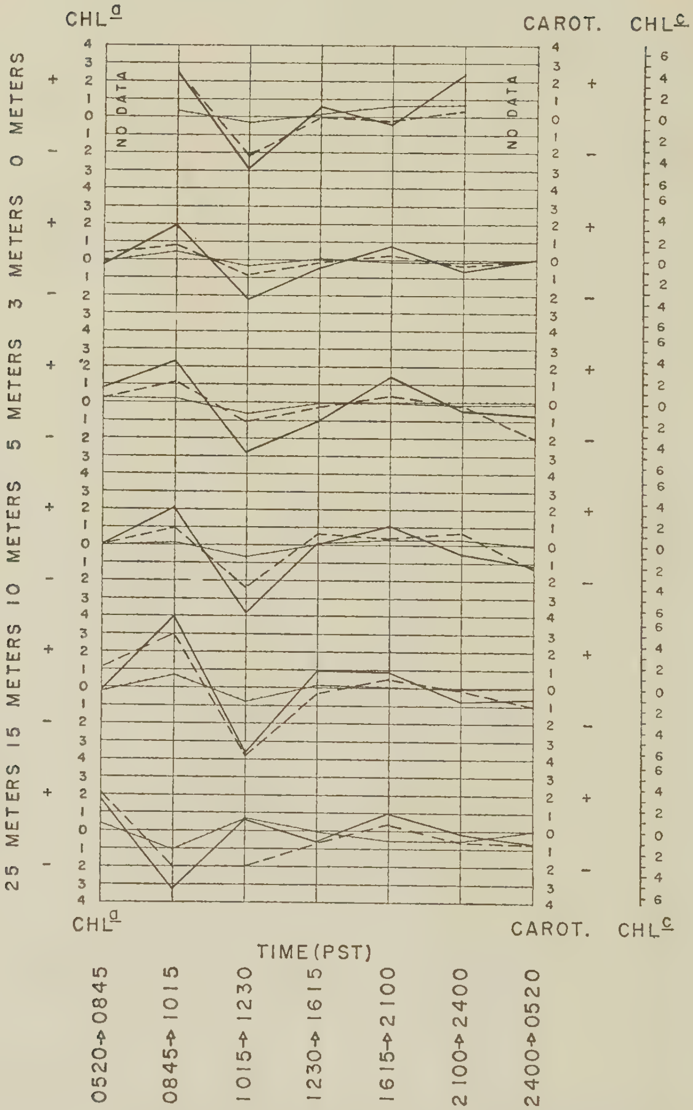

Figure 4. The rate of chlorophyll and carotenoid pigment synthesis (+) and decomposition (—). Units are 10^{-8} milligrams or specific plant pigment units per cell per hour. Solid line is chlorophyll *a*, dashed line chlorophyll *c*, dotted line carotenoid.

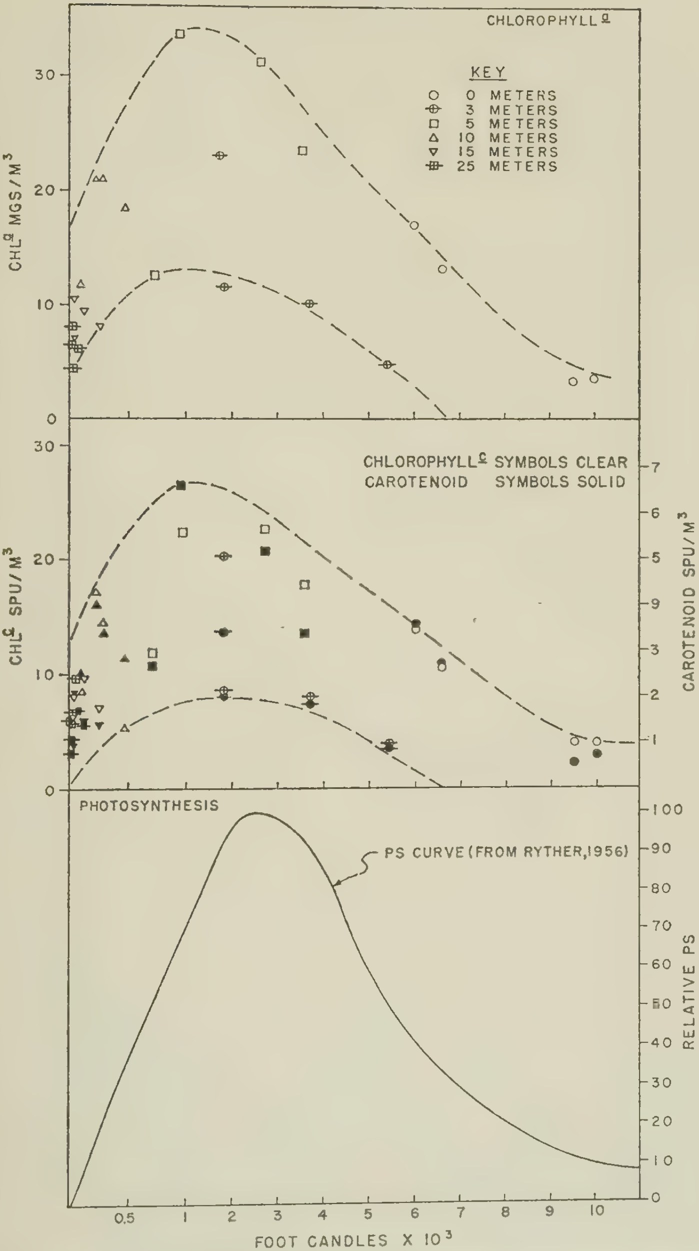

Figure 5. Relationship between *in situ* light and pigment concentrations at six depths.

Relationship between Light Intensities, Chlorophyll a, *Chlorophyll* c, *and Total Plant Carotenoid Values.* The largest concentrations of all pigments corresponded to *in situ* light intensities of approximately 1500 foot-candles (Fig. 5), the lowest corresponding to the highest *in situ* intensities of 10,000 f-c. Although the range in pigment concentrations is large for a given intensity, curves drawn through the extremes describe a curve which is comparable to Ryther's (1956) photosynthesis-light curve for natural populations of marine phytoplankton. Thus the shape of the pigment-intensity curves is interpreted to mean that phytoplankton near the surface during a brighter portion of the day were photosynthetically inhibited and that their pigment was bleached by the intense light. In contrast to this, phytoplankton in deeper water, exposed to light intensities below 1000 f-c, were light-limited.

In Fig. 6 the observed pigment content of cells are plotted against the *in situ* light intensities. Since development and decomposition of pigments within a cell is dependent upon both light intensity and its duration, a wide scatter is expected when these two measurements are taken simultaneously and are plotted against one another. A solid line encloses points of similar depth. Highest concentrations of chlorophyll *a* per cell occurred at light intensities between 100 and 2000 f-c while highest concentrations of carotenoid pigments per cell corresponded to intensities between 100 and 2500 f-c. Values of chlorophyll *a* per cell associated with high light intensities of 2000 were 60 $^0/_0$ lower than those associated with intensities of about 1500 f-c. In comparison, values of carotenoid per cell at high intensities (2500) were only 50 $^0/_0$ lower than those at optimal intensities (1500). Chlorophyll *c* quantities differ from those of the other two pigments in that high concentrations were found at both high and low intensities. The trend of points suggests that relatively low chlorophyll *c* values occur at intensities where the chlorophyll *a* per cell is highest.

Note the differential effect of light on pigments at different depths. Surface and near-surface phytoplankton underwent a wide change in light intensity with only a small change in pigment. In contrast, the pigment content of deeper phytoplankton was altered considerably by small changes in illumination. This distinction appears to be comparable to observations made by Harder (1930, 1933) on "light acclimatization" in aquatic plants. Thus the rates of photosynthesis and of pigment synthesis at different light intensities appear to be functions of the average intensity to which the cell is

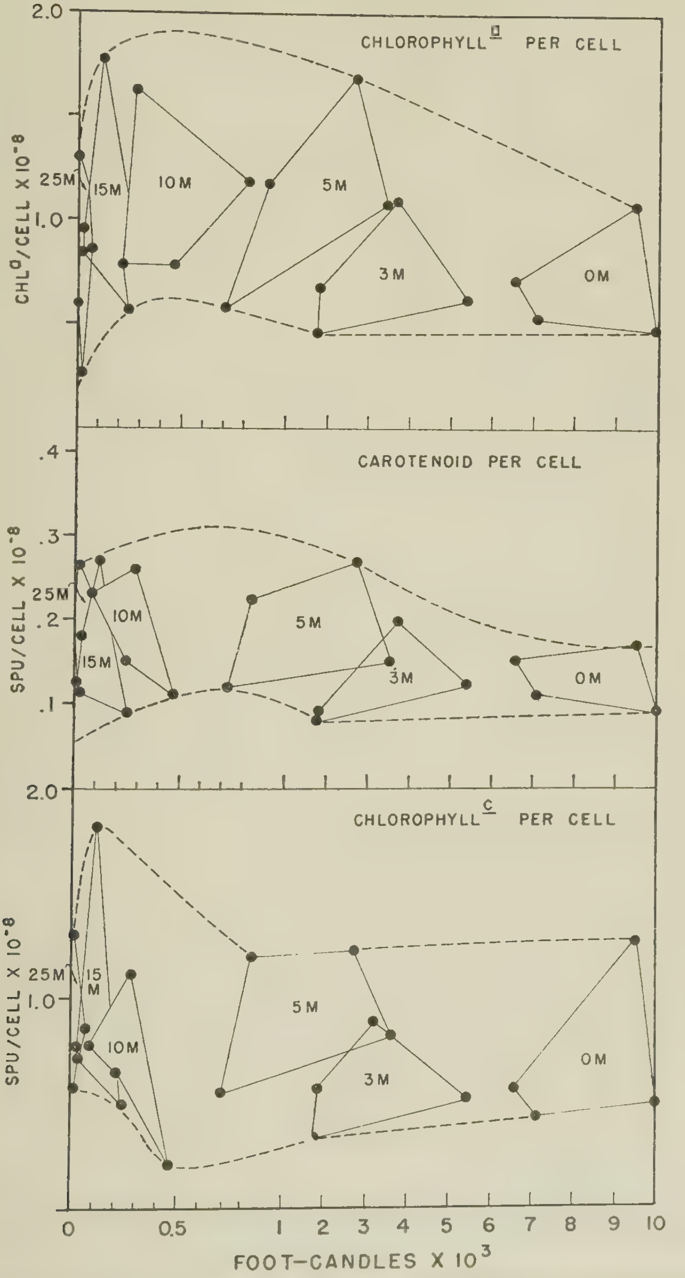

Figure 6. Relationship between *in situ* light and pigment concentrations per cell at six depths.

acclimated; hence phytoplankton living at deeper levels, in contrast to surface forms, synthesize pigment optimally at a lower intensity and show signs of bleaching earlier as the intensity increases.

Significance of Changes in Pigment Ratios. Halldal (1957) has pointed out that two ideas have been presented to explain the increasing proportion of carotenoid pigments relative to chlorophylls at higher light intensities. One hypothesis states that higher carotenoid pigments develop in intense light as a protective screen for the chlorophyll *a* pigment. The second idea, which suggests a differential rate of synthesis and bleaching, is more applicable in accounting for changes in the pigment ratio observed in the surface waters of East Sound. However, these pigment changes do not appear to follow a pattern indicative of chromatic adaption. Indeed, at times lower Chl *a*:Carot ratios were found in deeper waters where green light would be the only portion of the spectrum available for photosynthesis. Nevertheless, the inconsistency of the Chl *a*:Carot ratio makes the wavelength utilization theory seem doubtful. It seems more logical to interpret variations in the Chl *a*:Carot ratio as an accompaniment to changes in the cellular composition of phytoplankton. It has been shown that changes in cellular nitrogen in cultures of marine phytoplankton are associated with a change in the proportion of chlorophyll and carotenoid pigments (Yentsch and Vaccaro, 1958). This familiar process of nutritional chlorosis in plants involves a general loss of plant pigment where the more rapid loss of chlorophyll and its protein complex, as compared to the slower decomposition of carotenoid pigments, changes the proportion of pigments. Hence it appears that a light-induced chlorosis is not different from a nutritional one, since the level of cellular nitrogen is indirectly independent on light through photosynthesis.

The difference between light intensity curves for chlorophyll *a* and for chlorophyll *c* suggests that chlorophyll *c* may serve as a precursor pigment of chlorophyll *a* since low values of chlorophyll *c* were at times found at light intensities optimal for chlorophyll *a*. Further support of the precursor function of chlorophyll *c* comes from Granick (1949) who has observed that the structure of chlorophyll *c* is more closely identical to protochlorophyll in higher plants than to chlorophyll *a*.

Diurnal Chlorophyll-Photosynthesis Curves. Some workers have felt that diurnal changes in the chlorophyll content of natural populations are due to internal rhythms (see Rabinowitch, 1945: chap. 15) rather than to changing light intensities. The diurnal pigment variations observed in this study lead us to conclude that light is the causative factor. Since photosynthesis is a function of chlorophyll concentration at light intensities up to saturation, it would appear that Yentsch and Ryther's (1957) conclusion is correct, *i. e.*, that diurnal fluctuations of the photosynthetic capacity of natural phytoplankton populations result from changing chlorophyll content within the population and not from internal rhythms, as suggested by Doty and Oguri (1957). However, the magnitude of the diurnal curve and the vertical distribution of phytoplankton pigments can be expected to be modified by both ecological and physiological factors. For example, the amount of pigment synthesized or decomposed depends on the duration as well as the intensity of the light reaching the cells. Therefore, cells held in surface waters by marked stability in the water column will be bleached more rapidly in intense light than a cell moving about in a mixed layer. Also, varying intensities of light arising from cloud interference will certainly lower the average intensity reaching each cell. The degree to which the cellular content of pigment is altered will be affected also by the previous light history as well as by the age of a cell. Cells growing at low light intensities will be more sensitive to light changes than those growing in high intensities. Furthermore the saturating light intensity for both chlorophyll synthesis and photosynthesis is temperature dependent, and both would be lower in colder than in warmer waters. Lastly, the inconsistency in periodicity curves could result from nutritional causes, since the amount of photosynthesis as well as chlorophyll synthesis depends on the availability of nutrients (see Ketchum *et al.*, 1958; Yentsch and Vaccaro, 1958); at optimal light intensities pigment synthesis is markedly reduced by depletion of available nutrients from a culture medium. In summary, different conditions of either light or temperature or nutrients can be expected to modify the daily periodicity curves for chlorophyll and photosynthesis.

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